The AIS wavefront sensor

An in-situ optical test via localized wavefront curvature sensing

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[2] Sematech
[3] Intel
[4] CNSE, University at Albany

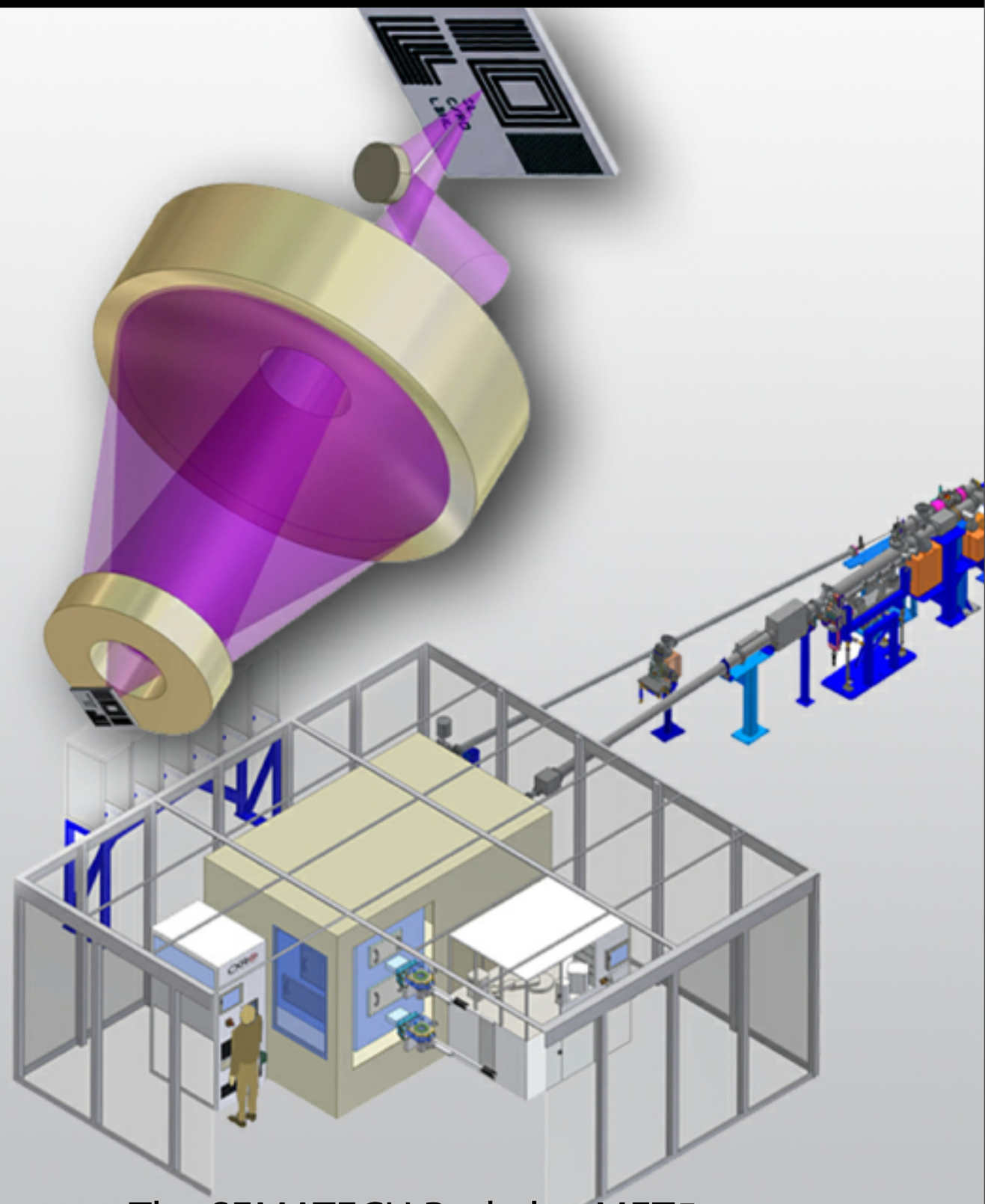
Motivation

1. High NA

2. Space

3. Cost

4. Convenience



The SEMATECH Berkeley MET5

Outline

1. Review of working principle

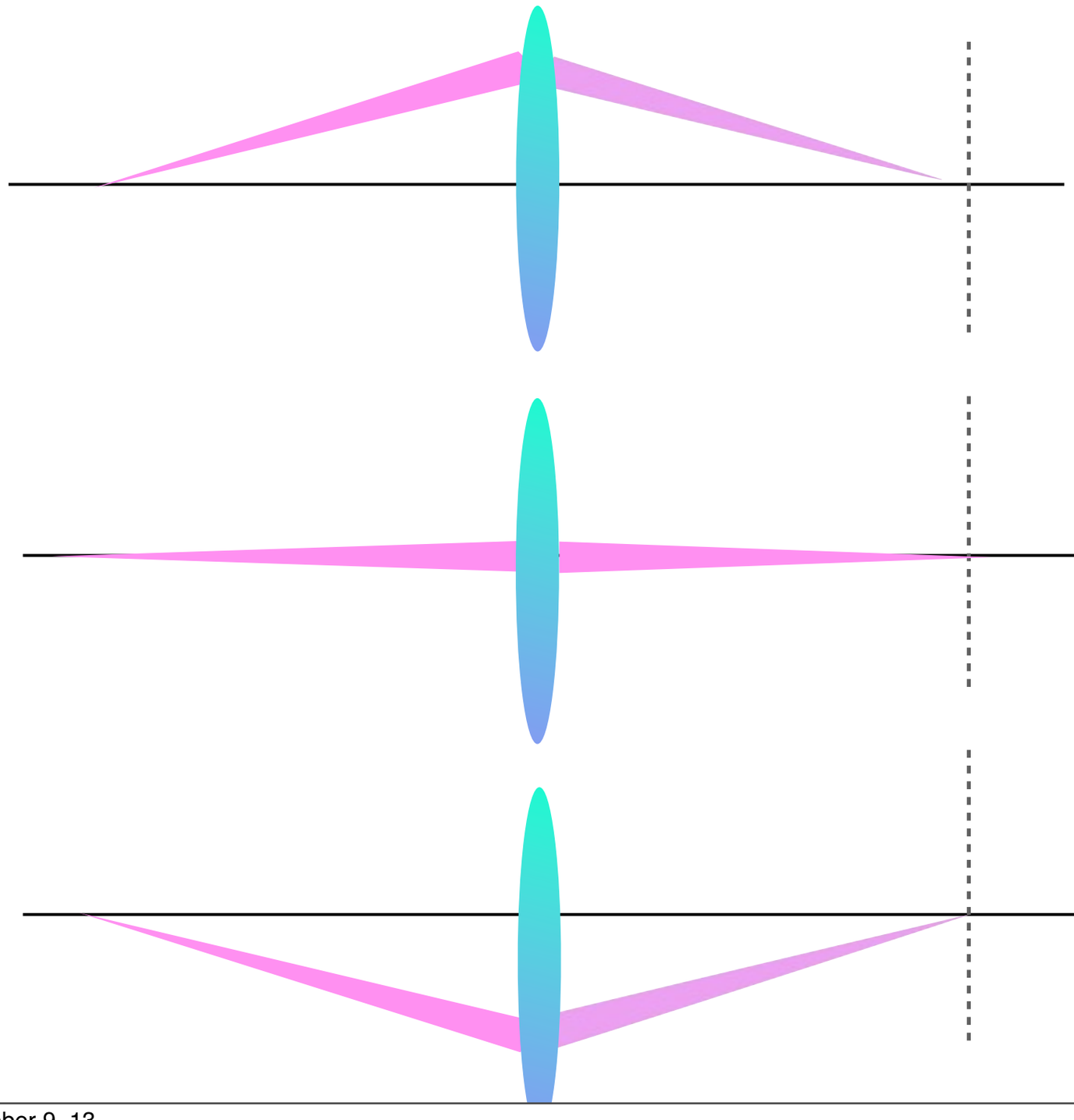
2. Experimental realization and design considerations

3. Recent results from optical prototype

Basic idea: Aberrated optical systems have nonuniform focus signatures over pupil

THE CENTER FOR X-RAY OPTICS

No aberrations



Basic idea: Aberrated optical systems have nonuniform focus signatures over pupil

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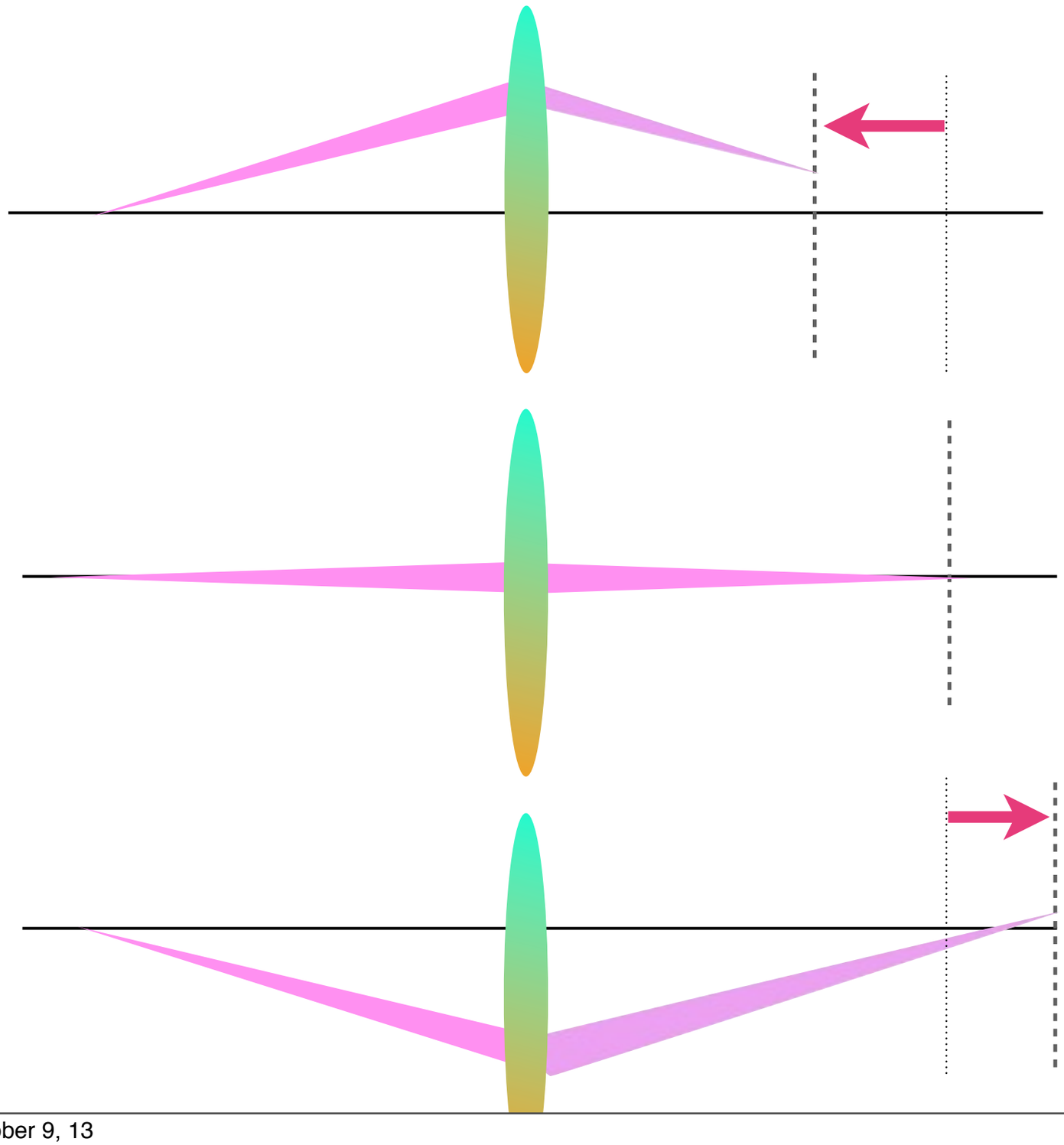
Aberrated



Zernike polynomials have curvature signature

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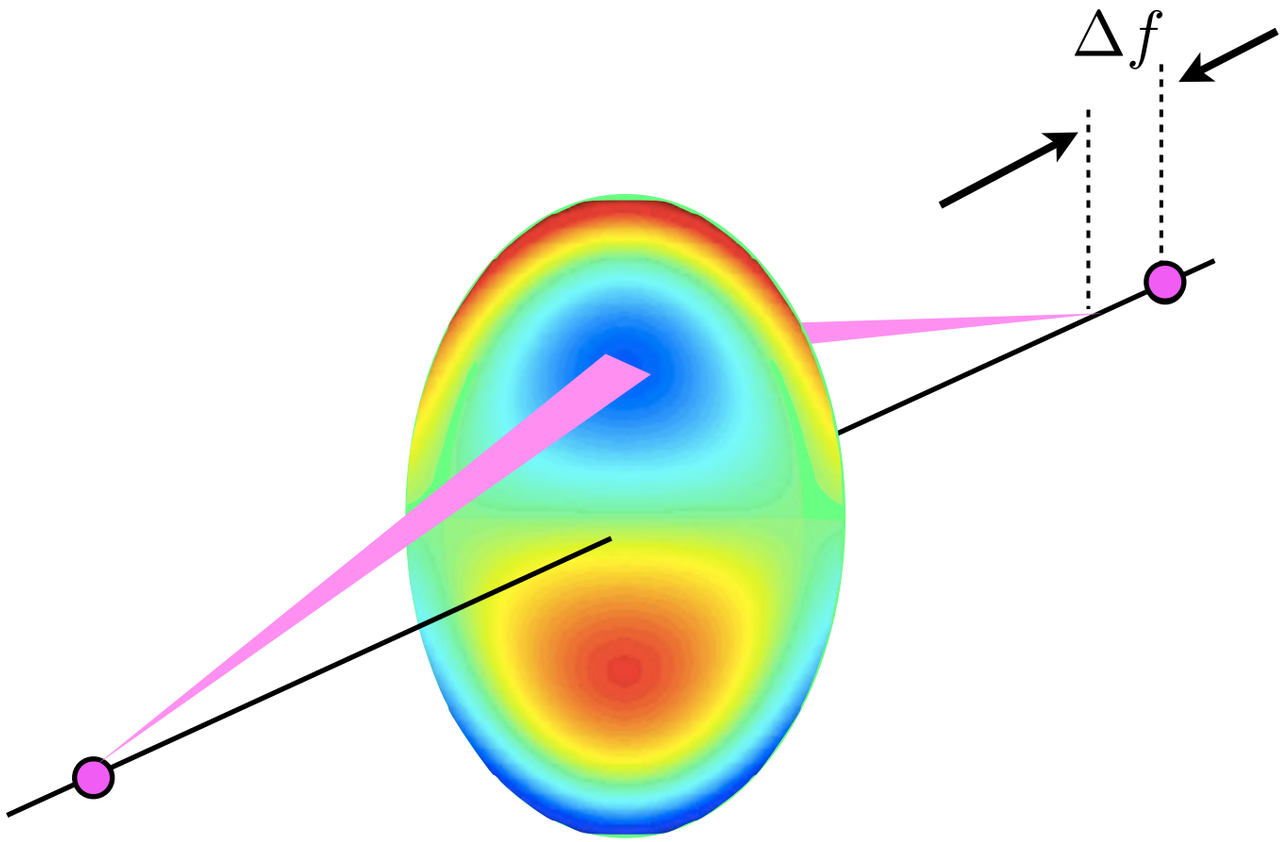
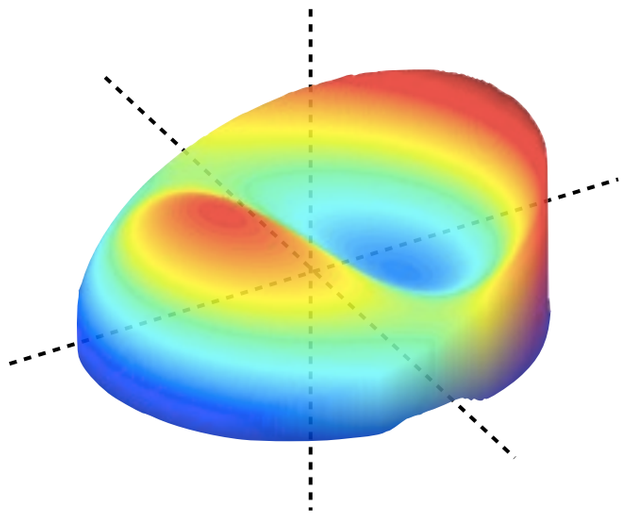
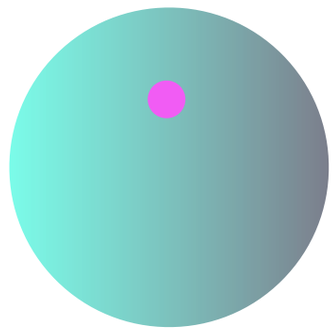
Z6: Coma





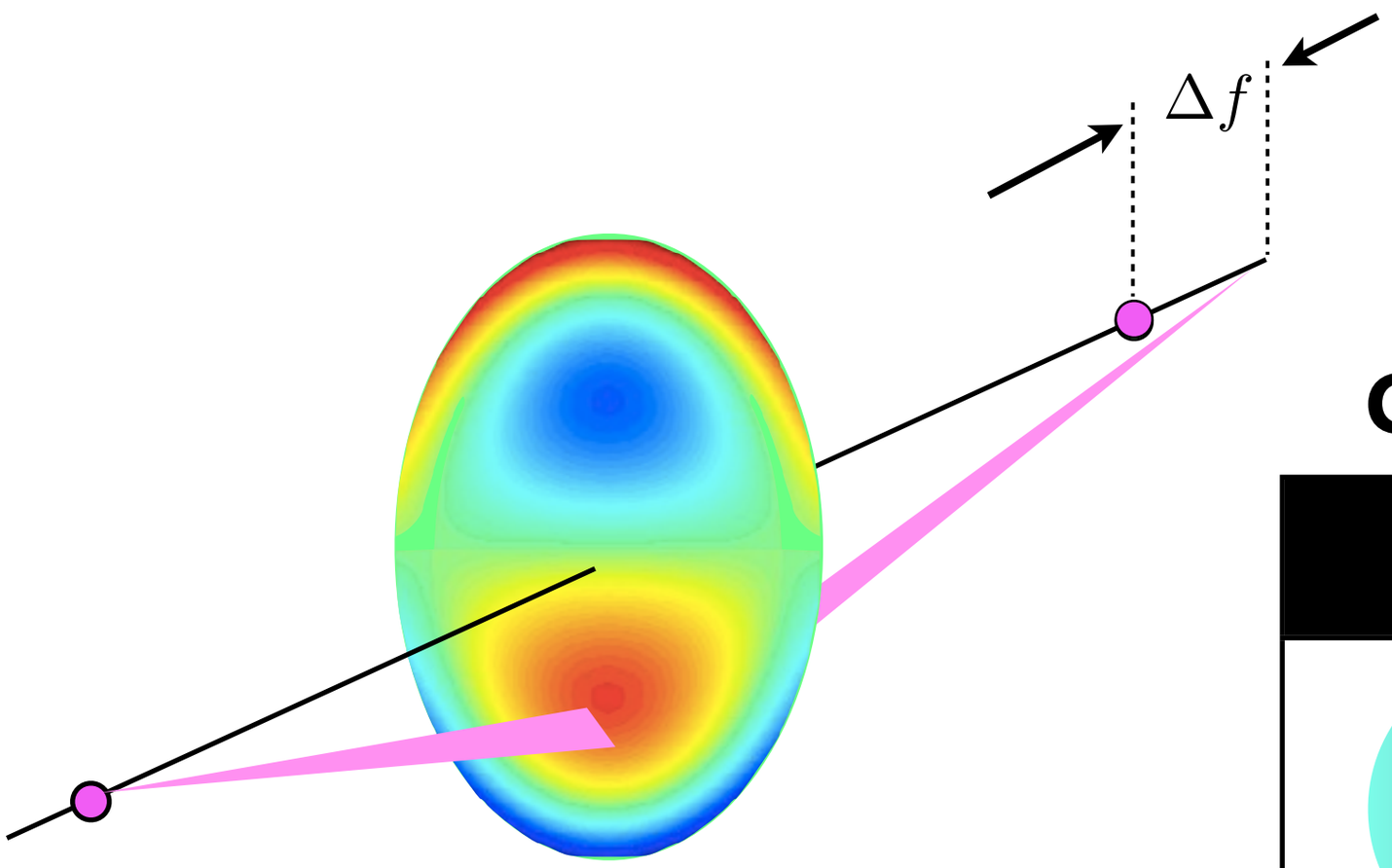
Curvature signature

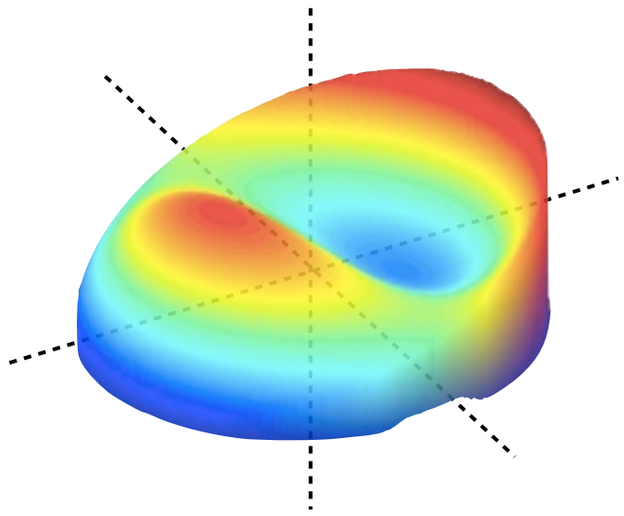
Probe	Δf
	–

Zernike polynomials have curvature signature

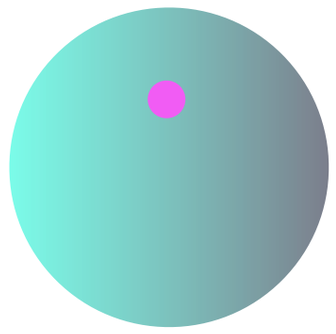
THE CENTER FOR X-RAY OPTICS

Z6: Coma

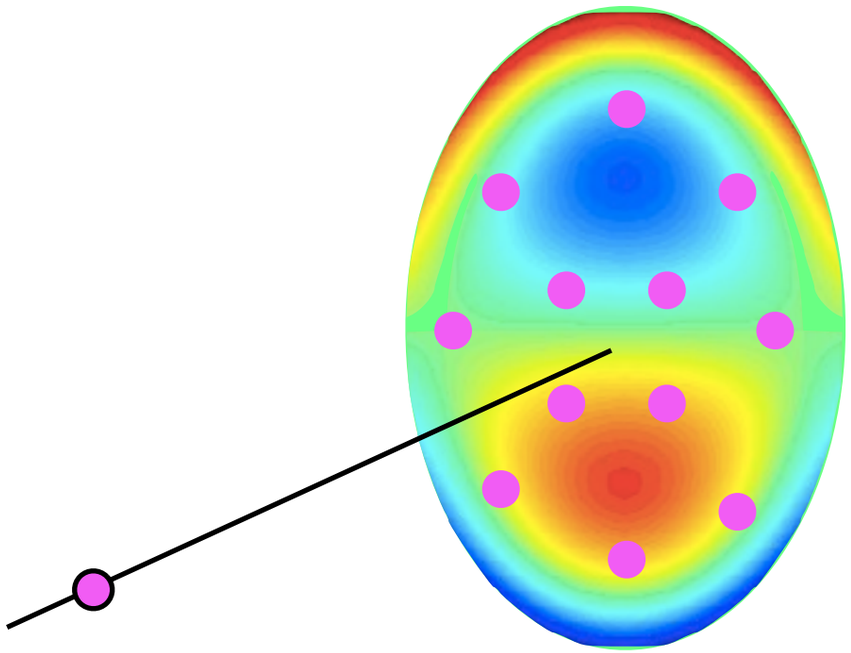




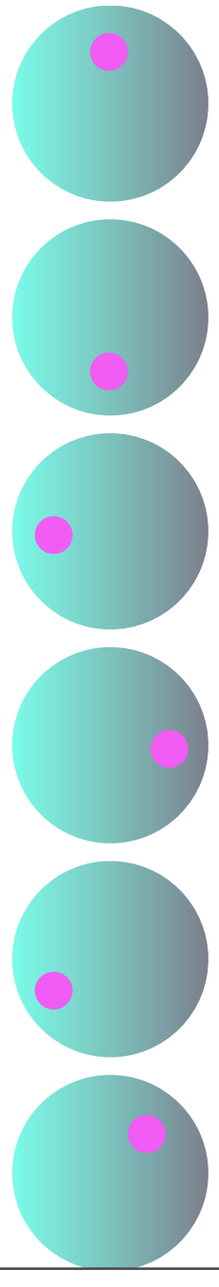
Curvature signature

Probe	Δf
	–

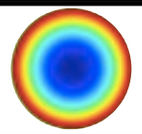
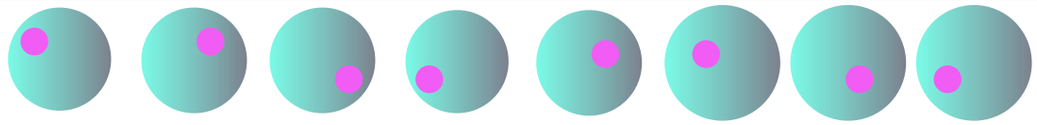
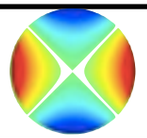
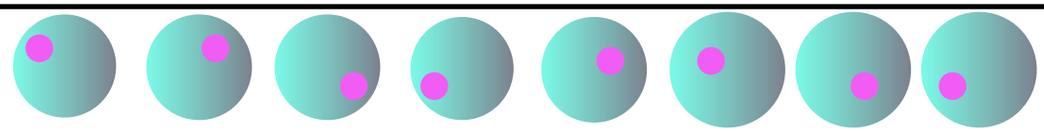
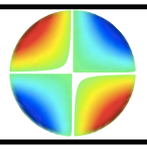
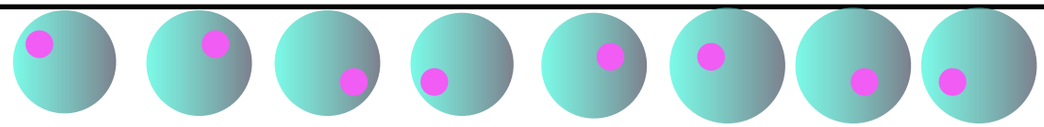
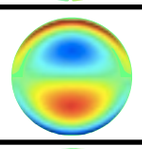
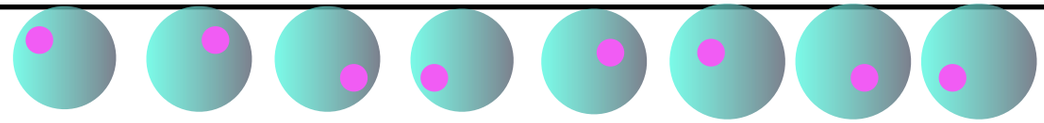
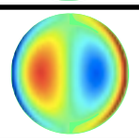
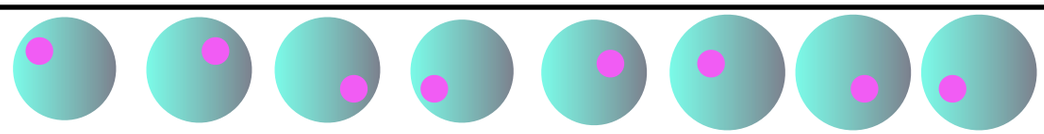
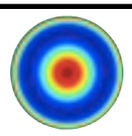
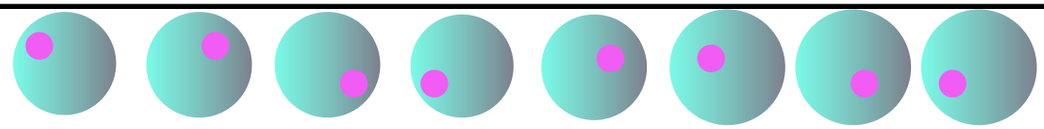
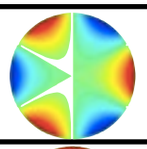
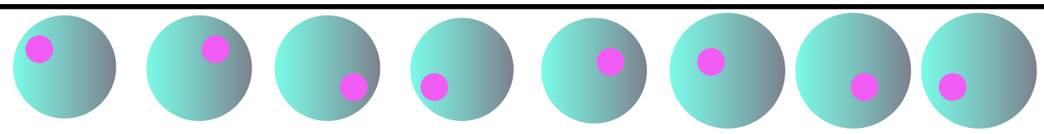
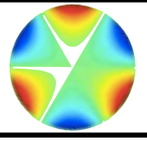
Z6: Coma



Curvature signature

Probe	Δf
	−
	+
	−
	−
	+
	−

Generate a curvature library

N	Aberration	Probe	Δf
3	Focus 		[+,-,+, -, -, +]
4	Stig 		[-,-,+, -, -, +]
5	Stig 		[-,-,+, +, -, +]
6	Coma 		[+,-,+, -, +, +]
7	Coma 		[+,+,+, -, -, +]
8	Spherical 		[-,+,+, +, -, +]
9	Trifoil 		[+,-,-, -, -, +]
10	Trifoil 		[+,-,-, +, +, +]

Curvature library

N	Aberration	Probe	Δf
3	Focus		[+,-,+, -, -, +]
4	Stig		[-,-,+, -, -, +]
5	Stig		[-,-,+, +, -, +]
6	Coma		[+,-,+, -, +, +]
7	Coma		[+,+,+, -, -, +]
8	Spherical		[-,+,+, +, -, +]
9	Trifoil		[+,-,-, -, -, +]
10	Trifoil		[+,-,-, +, +, +]

$$\bullet \begin{bmatrix} \end{bmatrix} = \begin{bmatrix} \Delta f \end{bmatrix}$$

Wavefront

Focus shifts

Curvature library

N	Aberration	Probe	Δf
3	Focus		[+,-,+, -, -, +]
4	Stig		[-,-,+, -, -, +]
5	Stig		[-,-,+, +, -, +]
6	Coma		[+,-,+, -, +, +]
7	Coma		[+,+,+, -, -, +]
8	Spherical		[-,+,+, +, -, +]
9	Trifoil		[+,-,-, -, -, +]
10	Trifoil		[+,-,-, +, +, +]

$$\dagger \bullet \begin{bmatrix} \Delta f \end{bmatrix} \approx \begin{bmatrix} \end{bmatrix}$$

Focus shifts

Wavefront

Wavefront sensor outline

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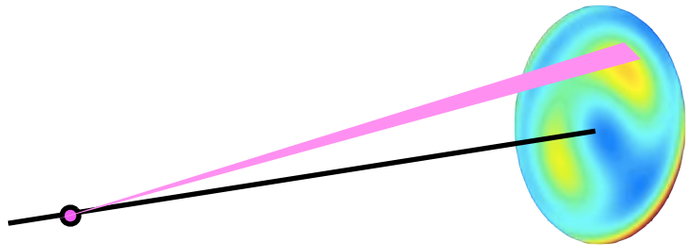
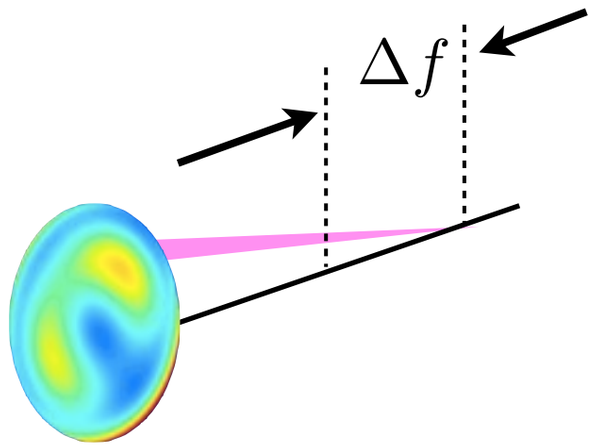
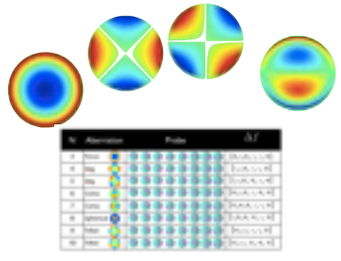
Step 1: **Probe** localized regions of the pupil

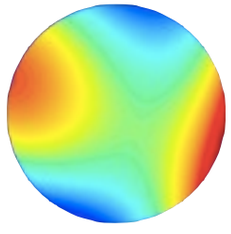


Step 2: Find the plane of **best focus** for each probe location

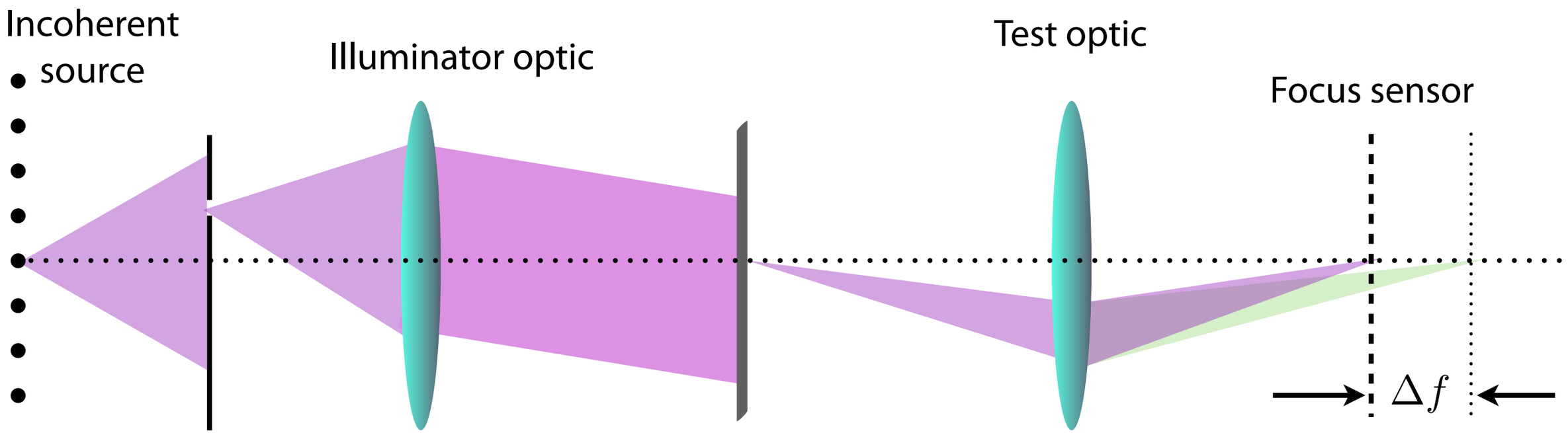


Step 3: Convert these focus shifts into an aberration map using **curvature library**

Δf →  →



Experimental realization and design



Offset monopole illumination

Grating orientation design considerations

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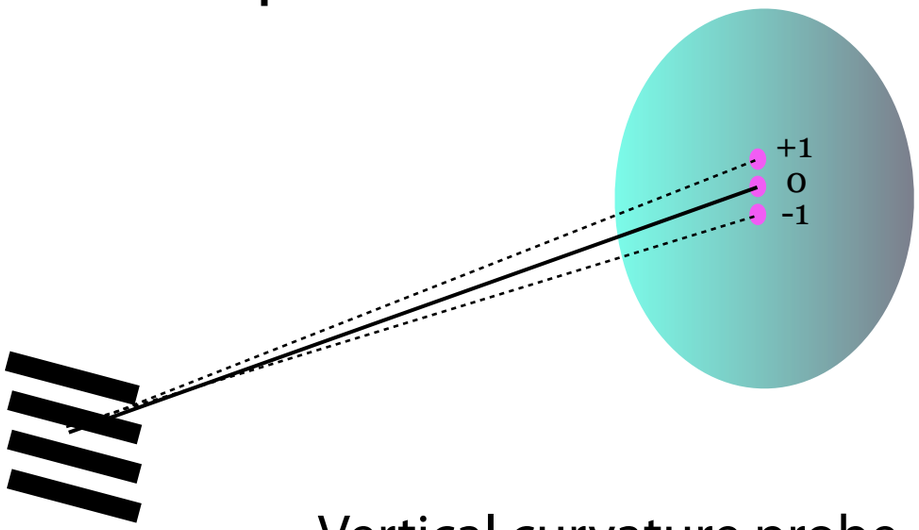
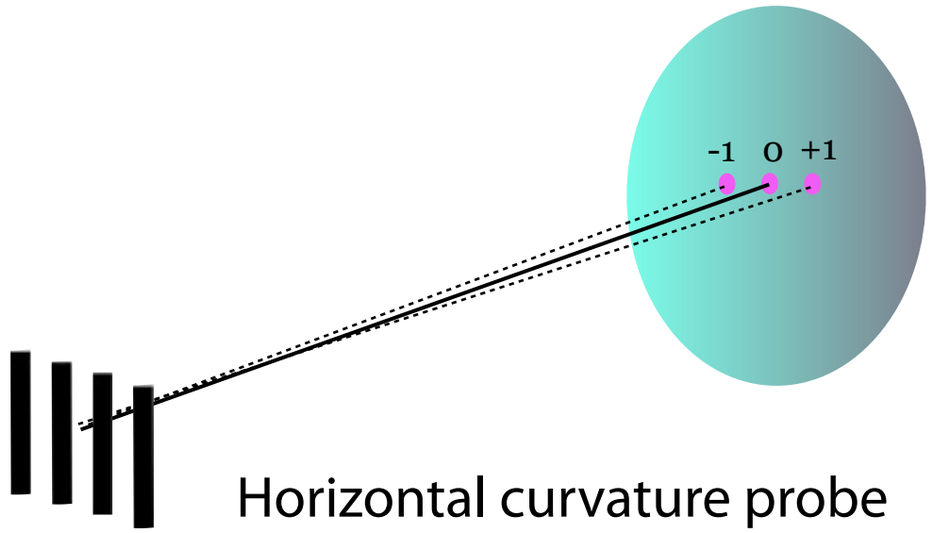
Curvature probe orientation determined by grating orientation

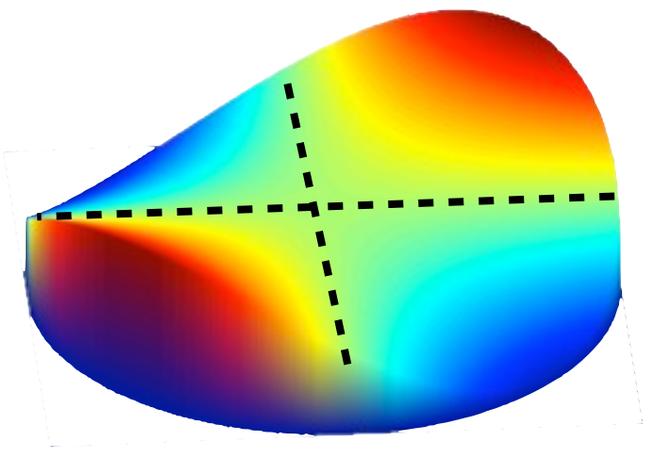


Vertical curvature probe

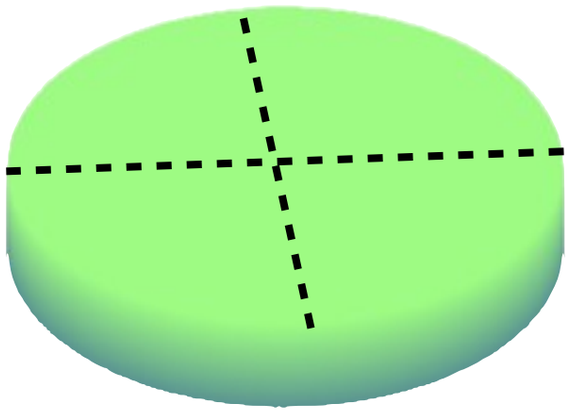


Horizontal curvature probe

Require enough orientations to make reconstruction well-conditioned



Z_5



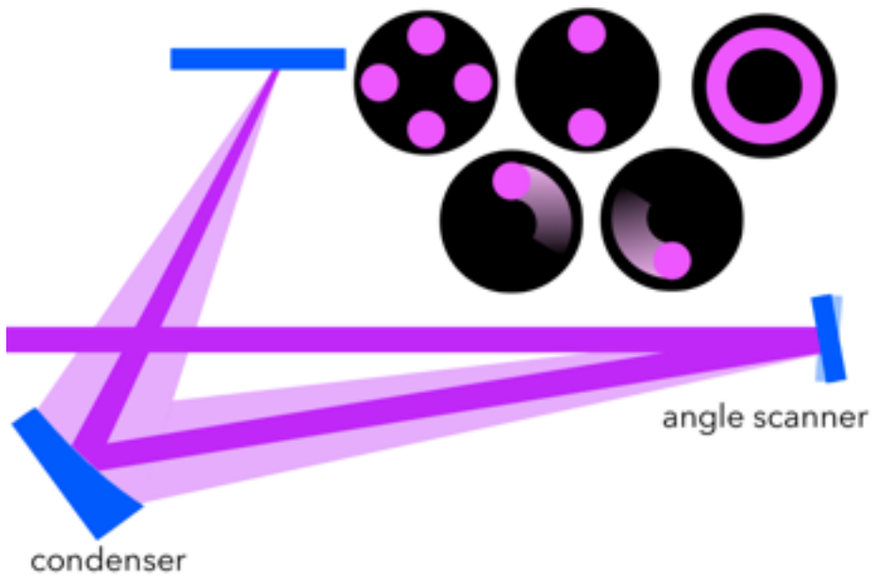
Z_0

Minimum # of orientations: 3

* 45-astigmatism has no curvature in x-y directions

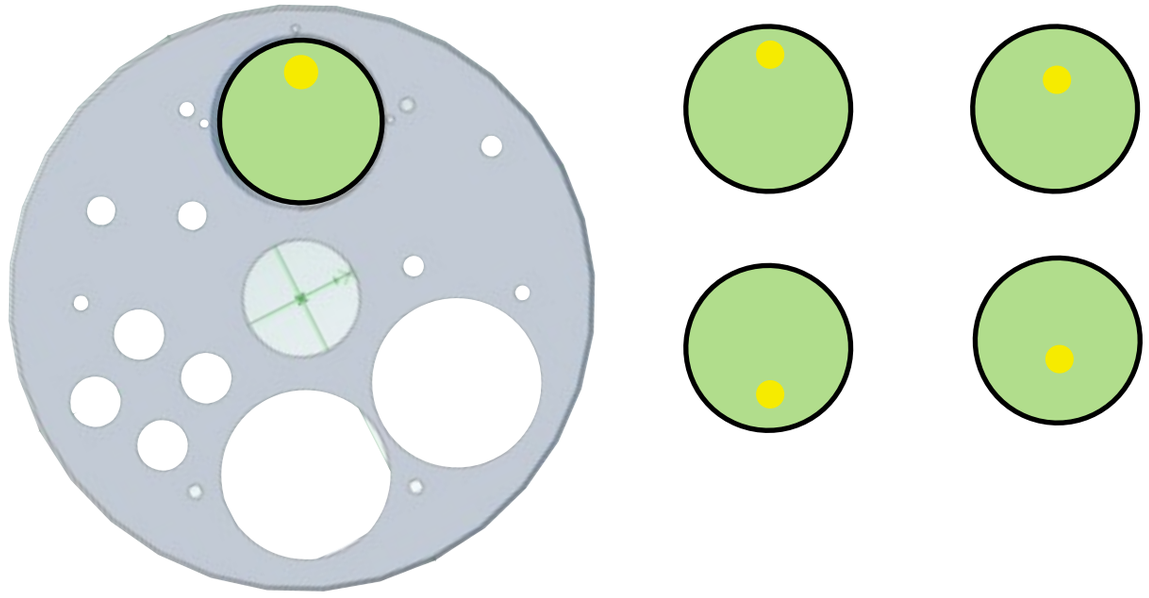
Illumination control

SEMATECH Berkeley MET



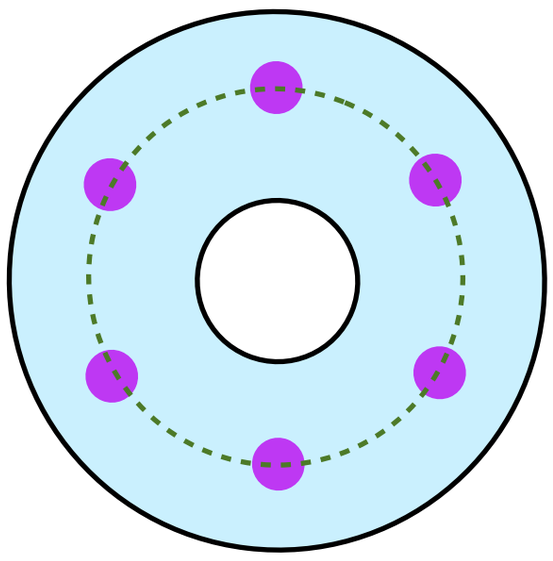
Programmable illumination via pupil scanners

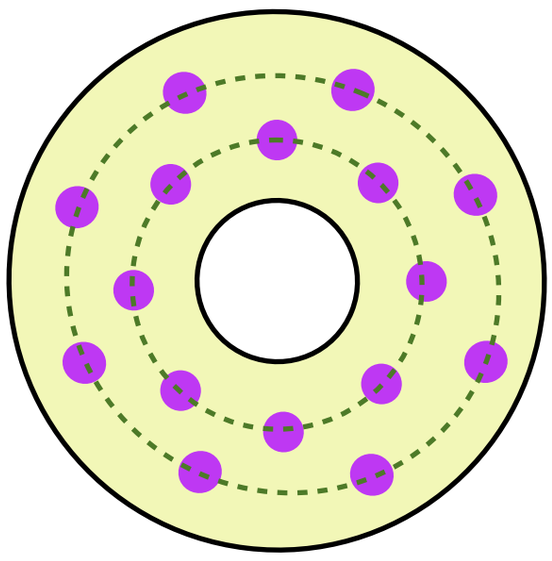
Albany MET



Pupil wheel with configurable illumination masks

Number of probe positions depends on size of Zernike reconstruction basis





Minimum # of probe positions:

8 Zernikes: **6 probes**

15 Zernikes: **16 probes**

Illumination control

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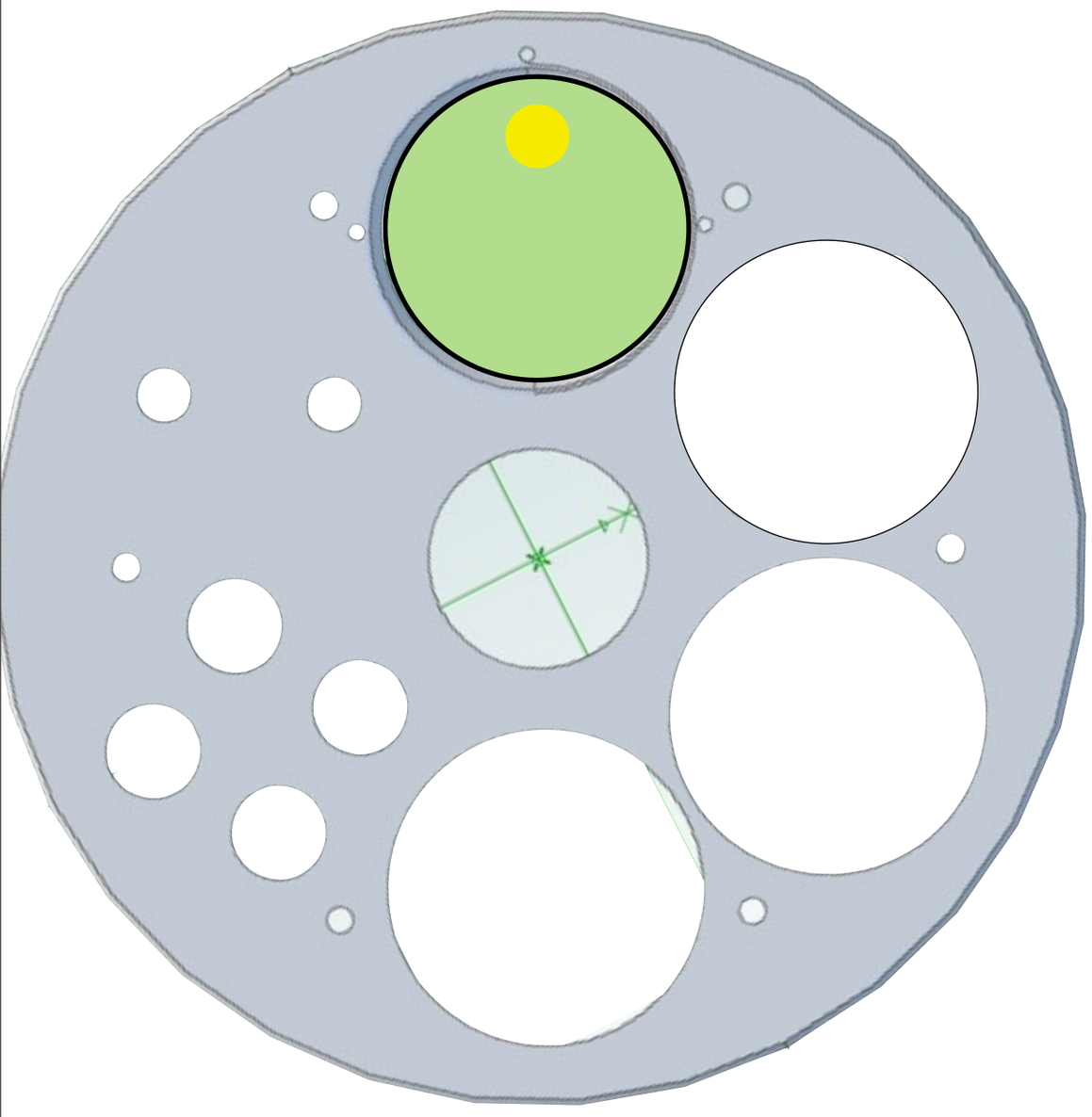
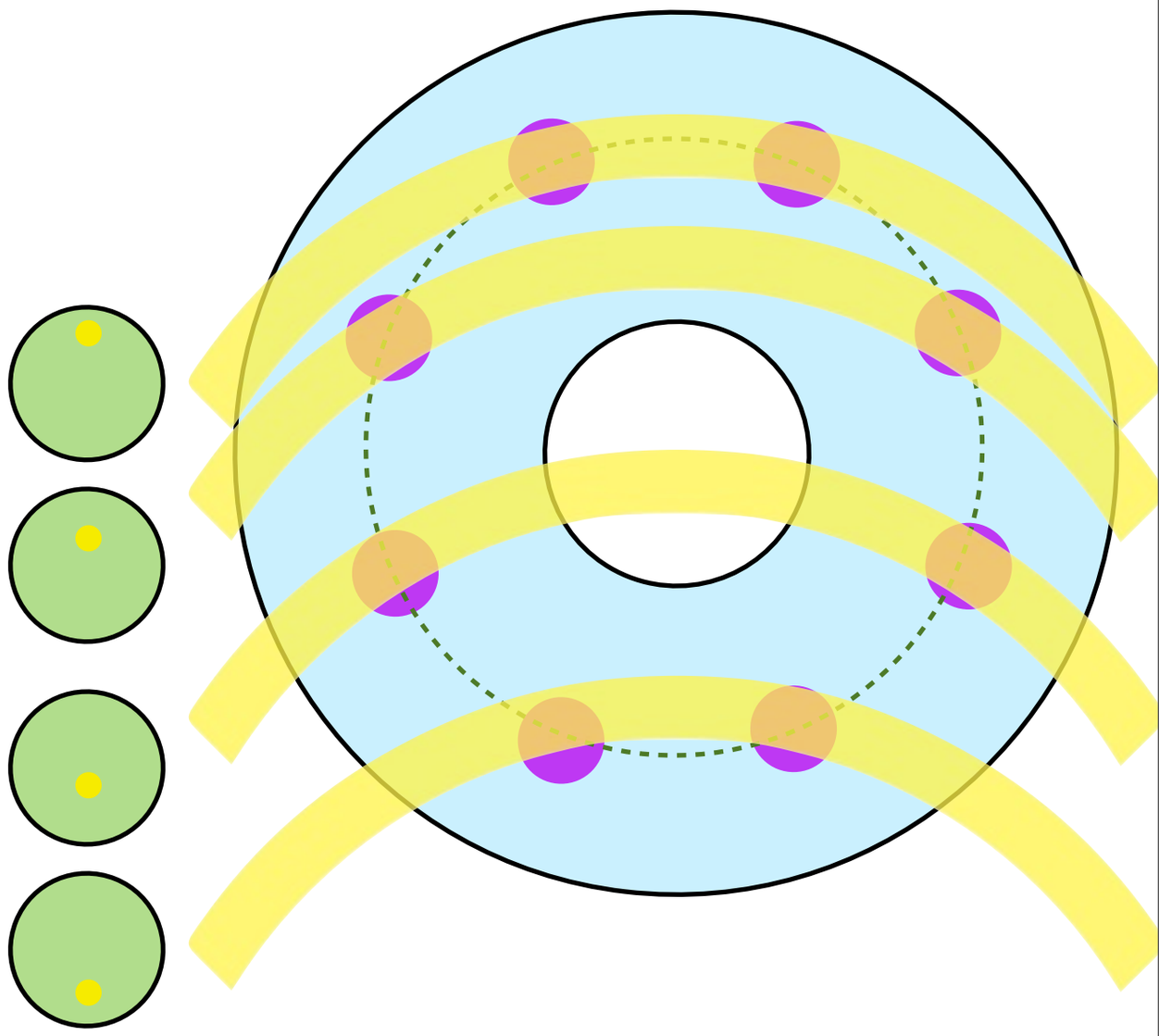
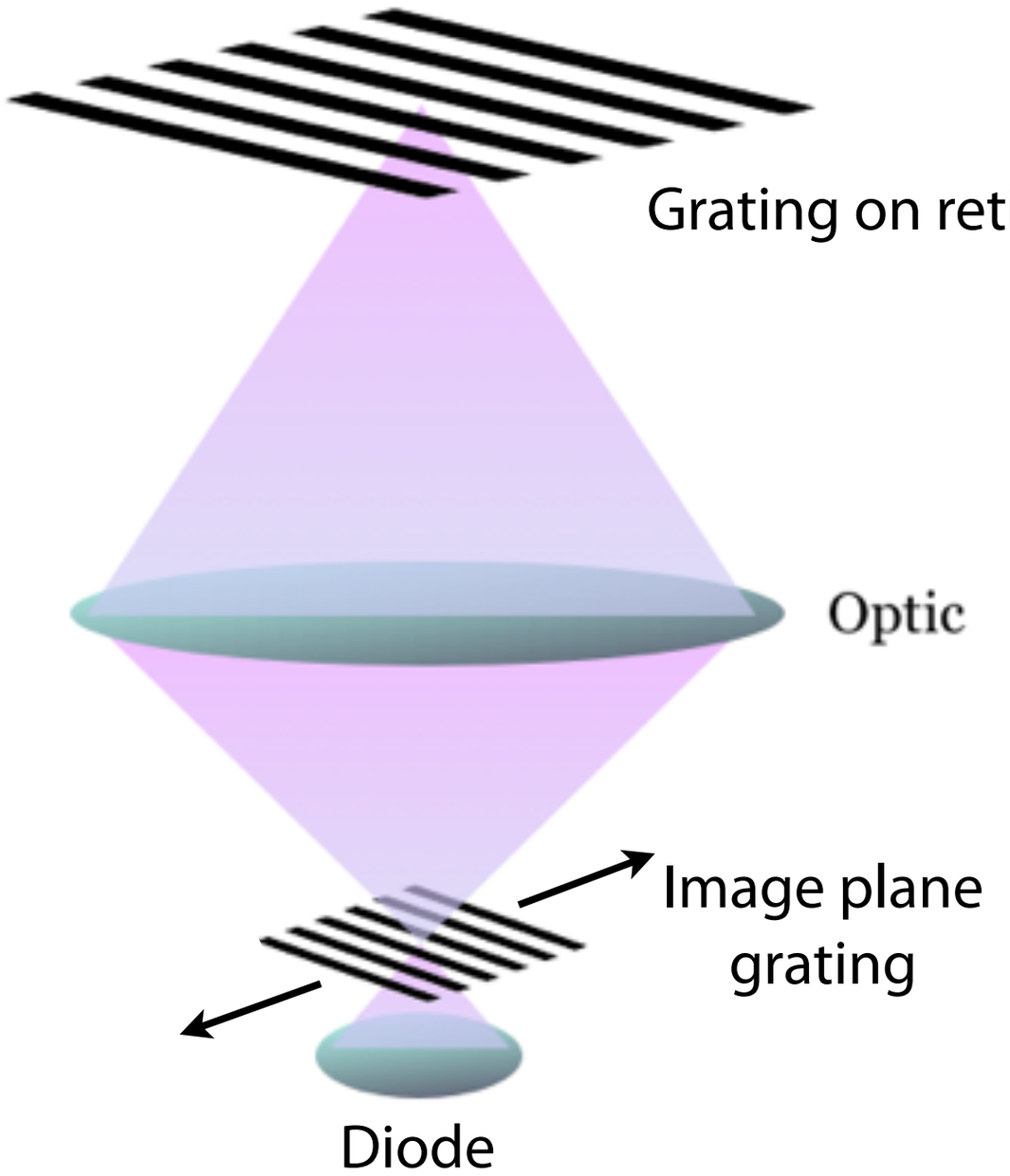
*** Number of probes is more important that their specific location**

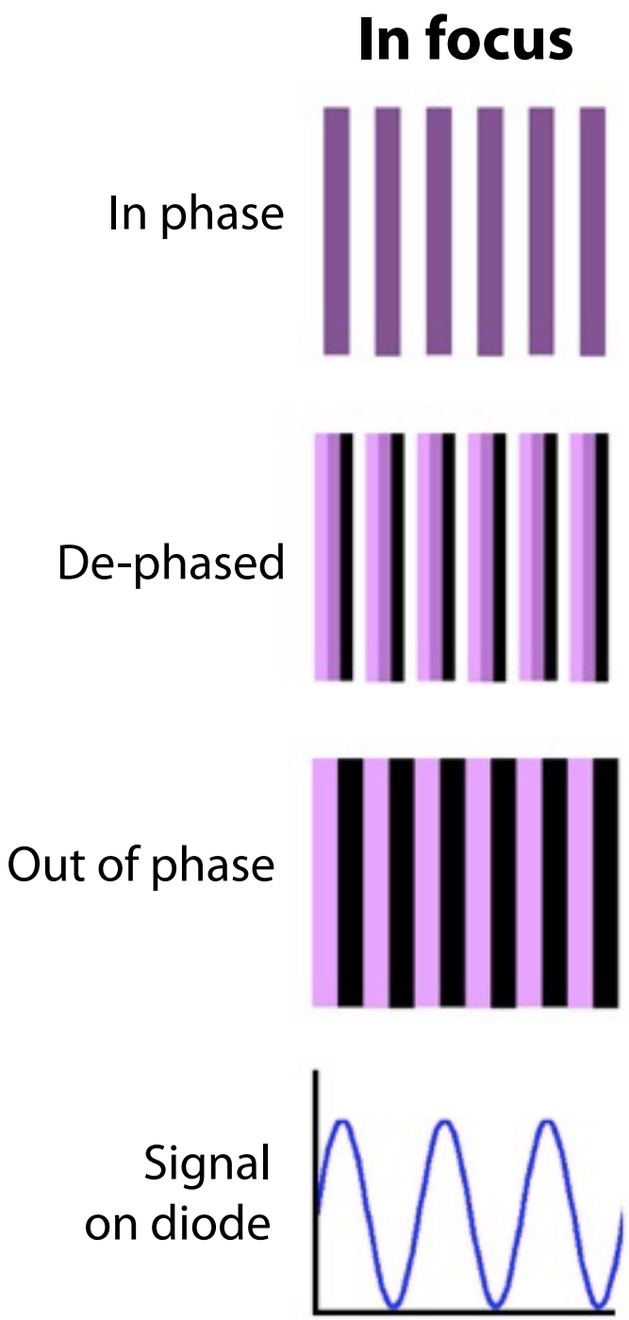
Albany MET3 pupil wheel



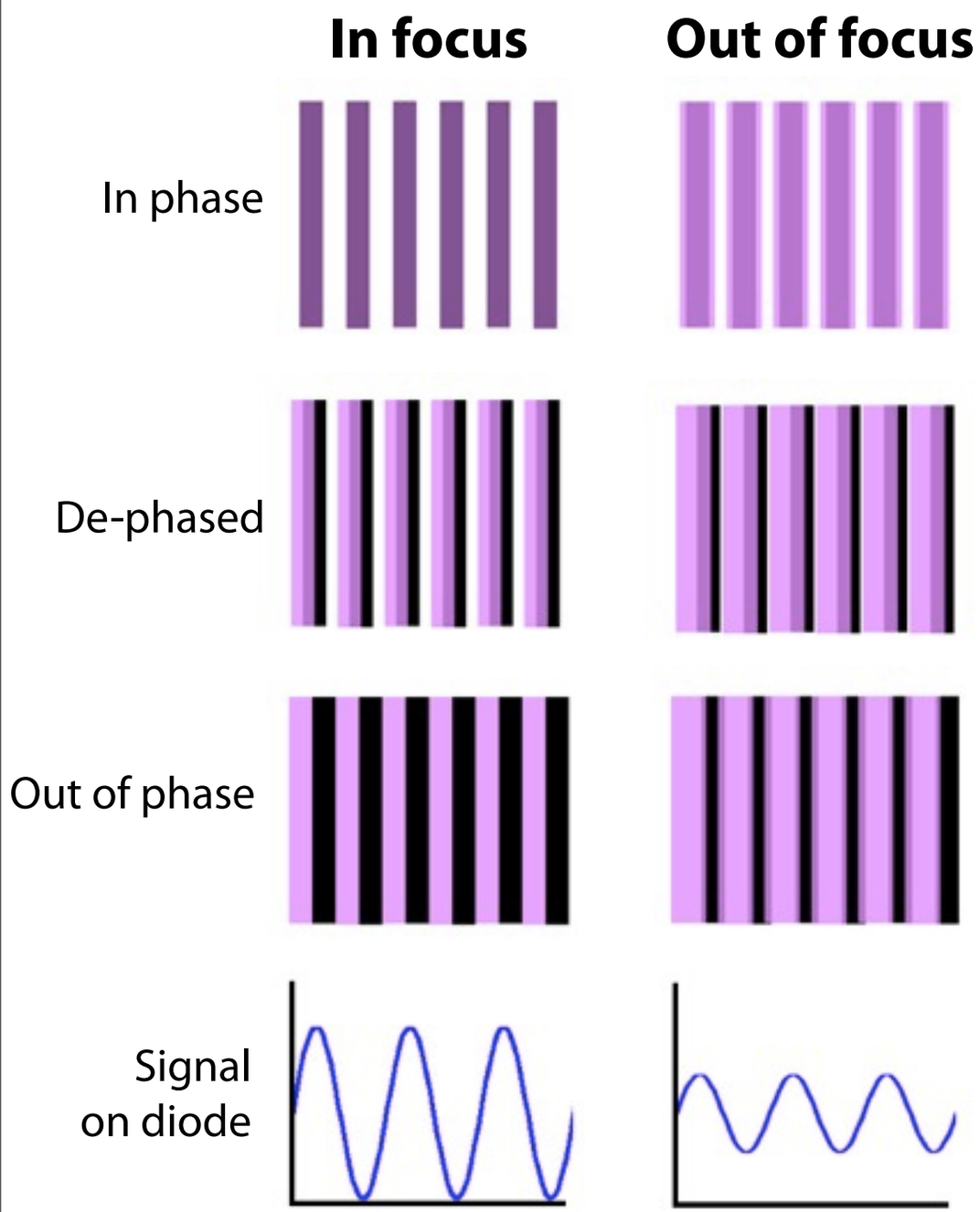


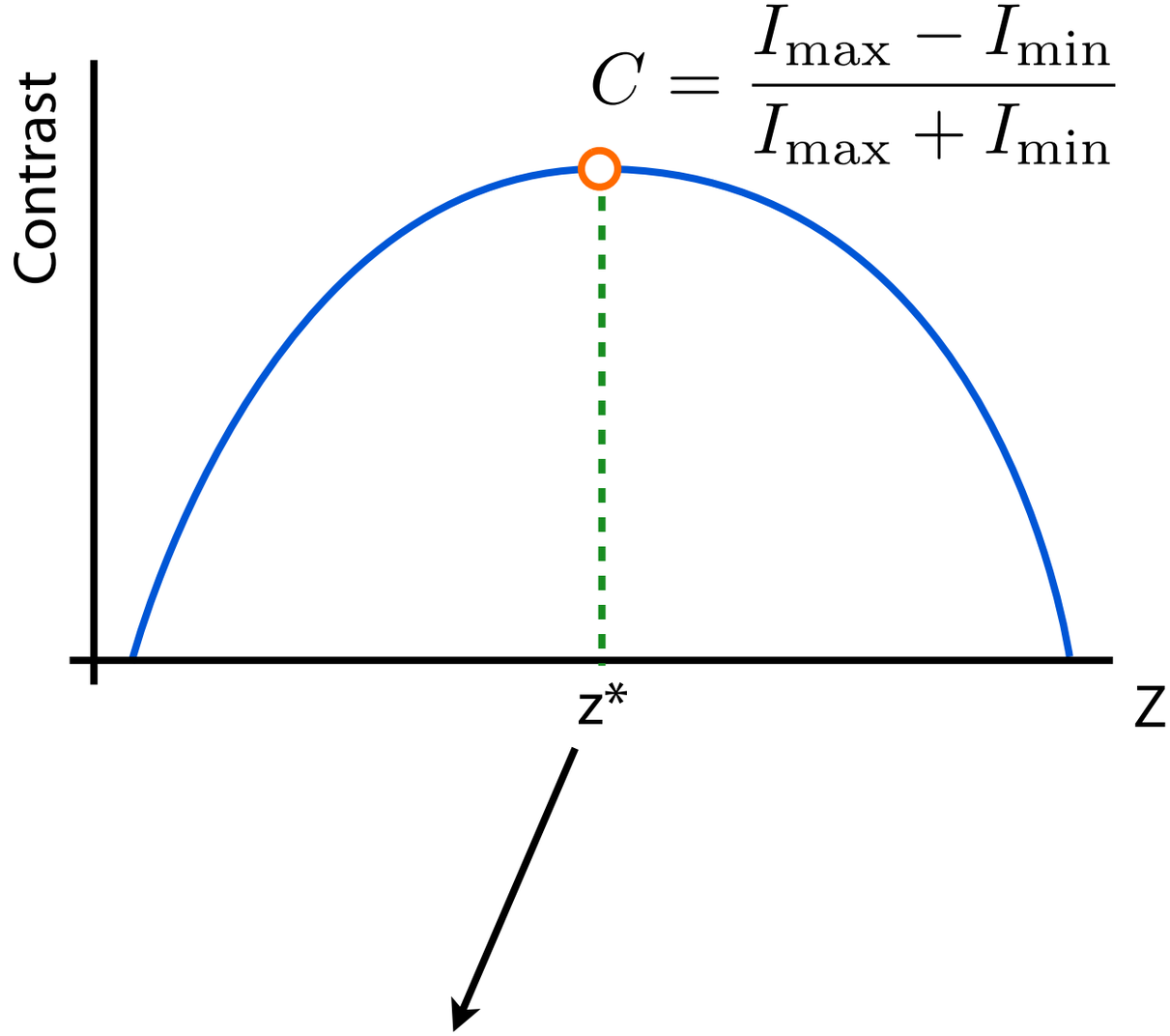
Focus sensor





Focus sensor





Best focus given by the z value that maximized the contrast of the diode signal modulation

Optimizing design for smallest errors

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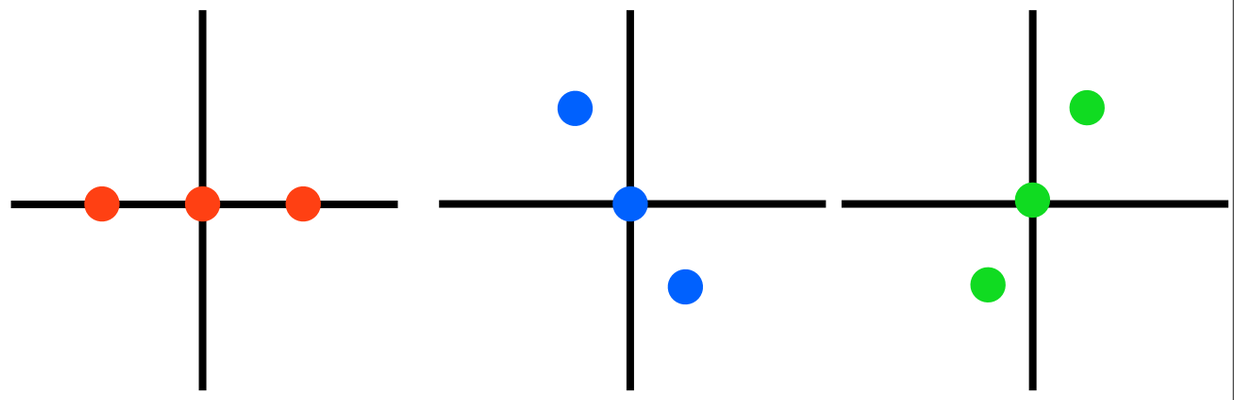
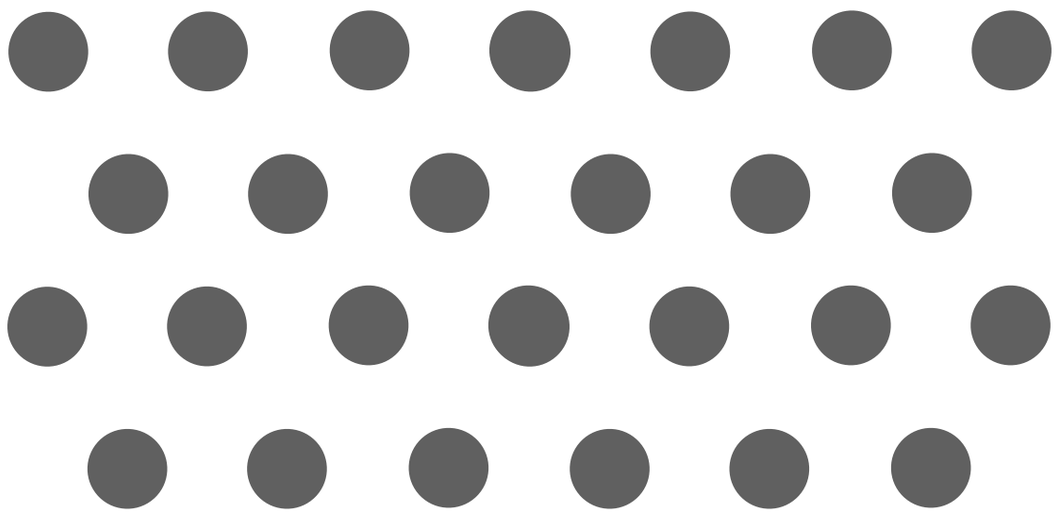
$g(x)$

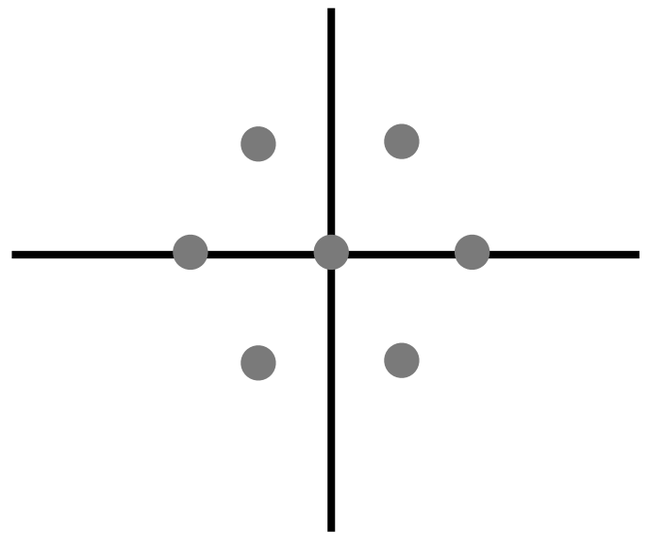
$G(f)$



$h(x)$

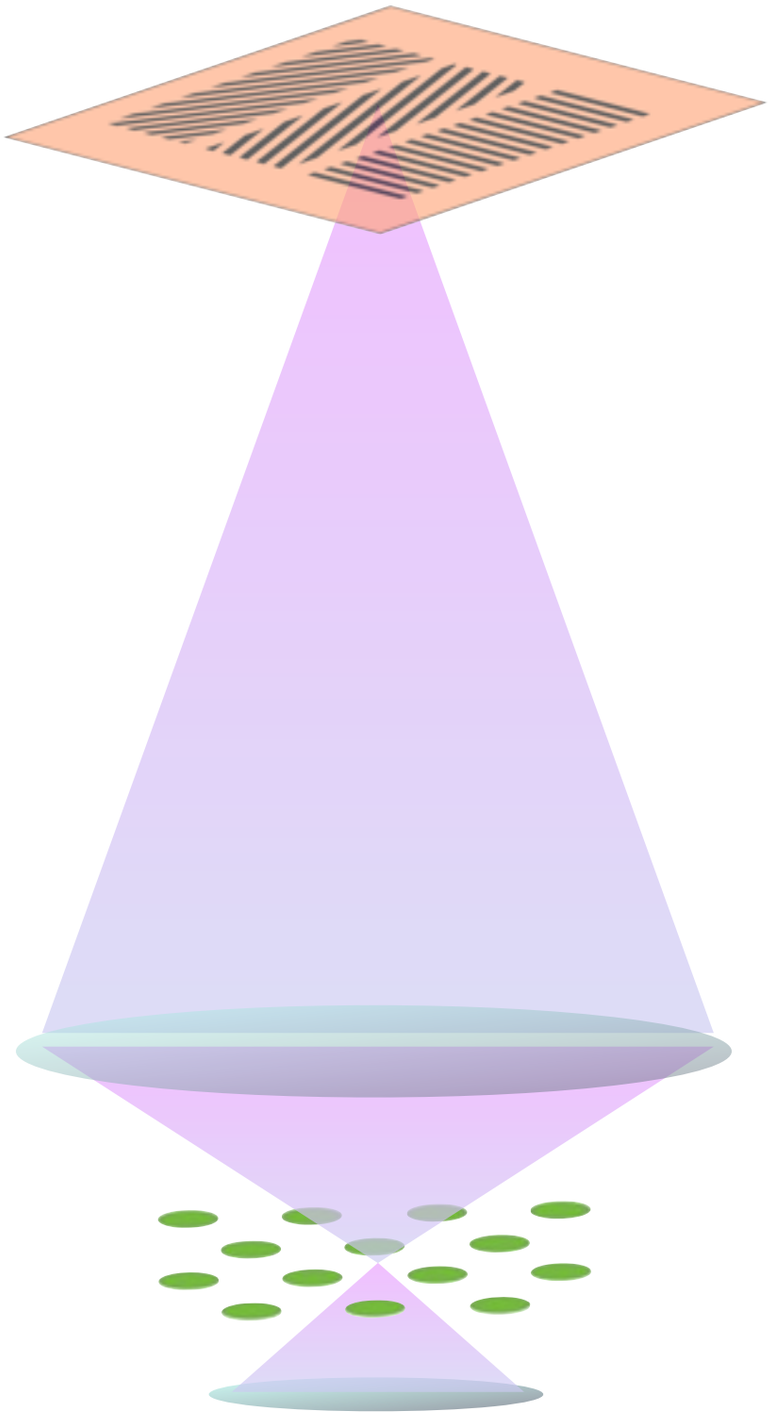


$H(f)$

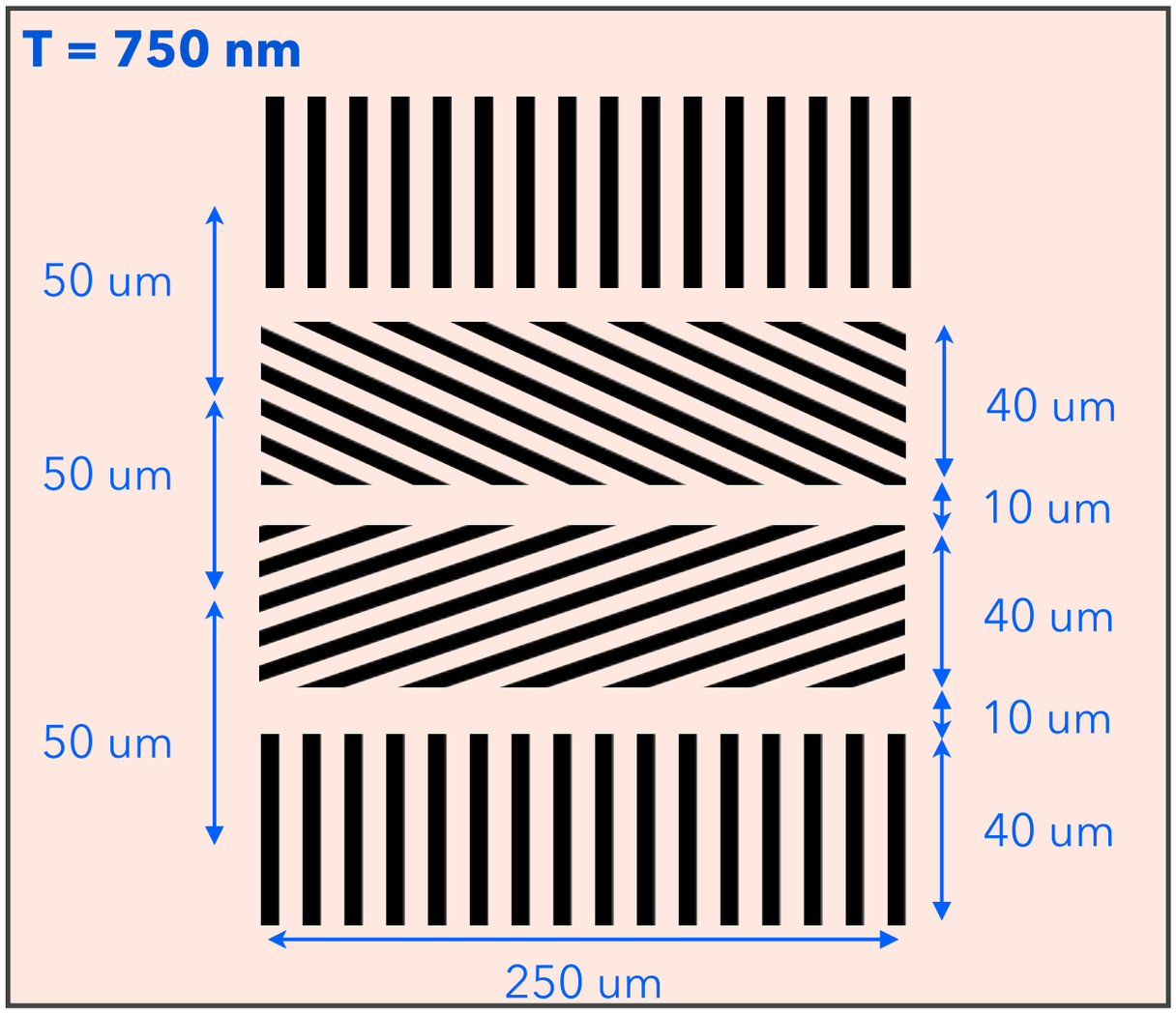


Hexagonal pinhole array is *simultaneously* compatible with all 3 grating orientations

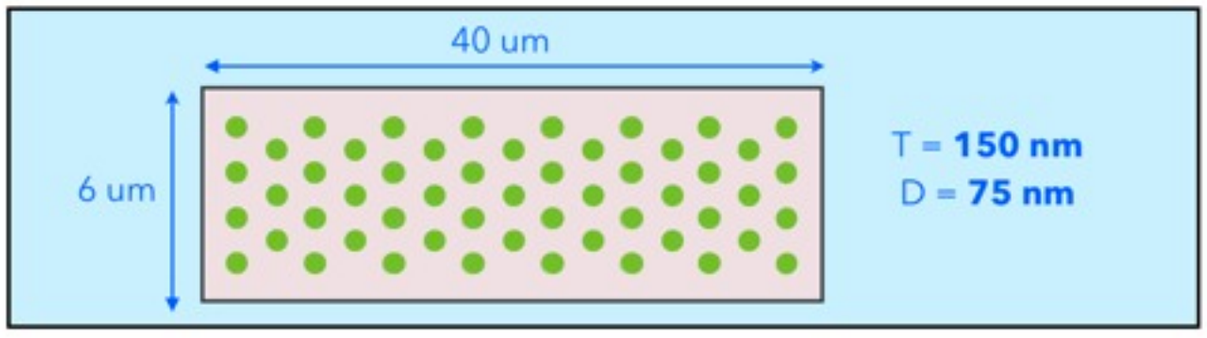
Mask design



Reticle-plane mask



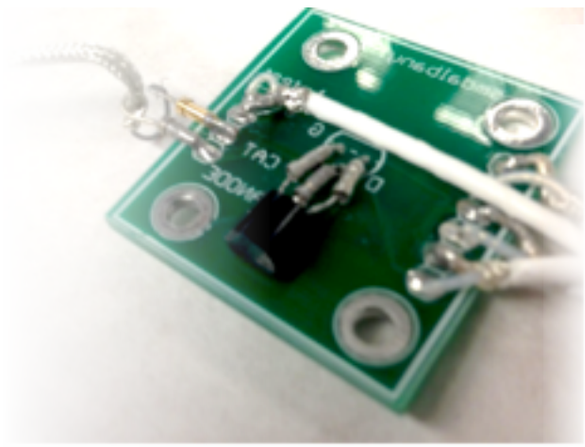
Wafer-plane stencil mask



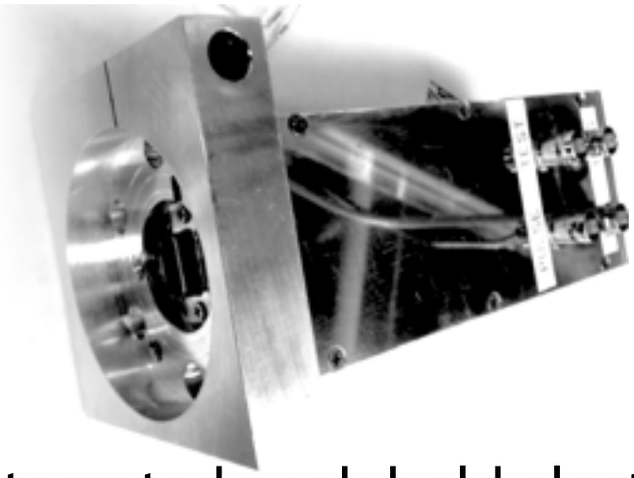
AIS detector noise test

THE CENTER FOR X-RAY OPTICS

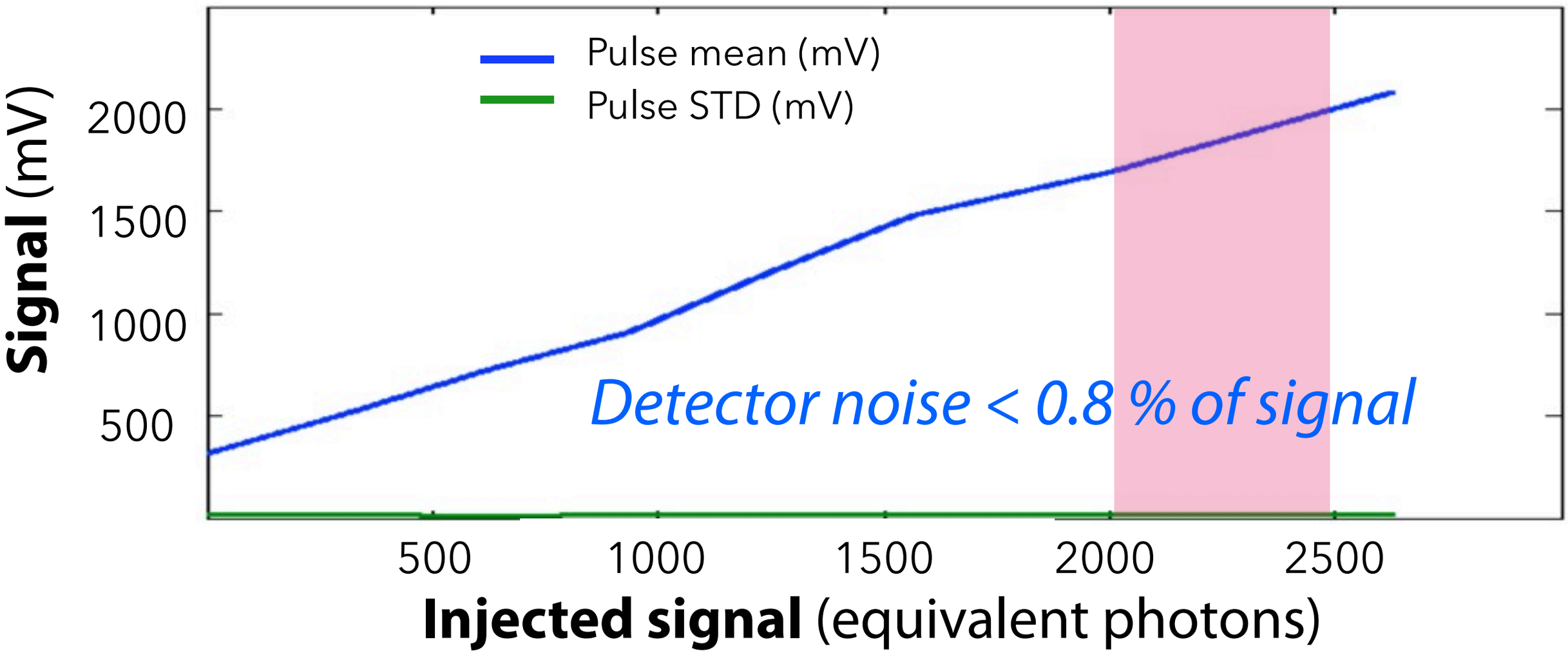
IRD EUV diode



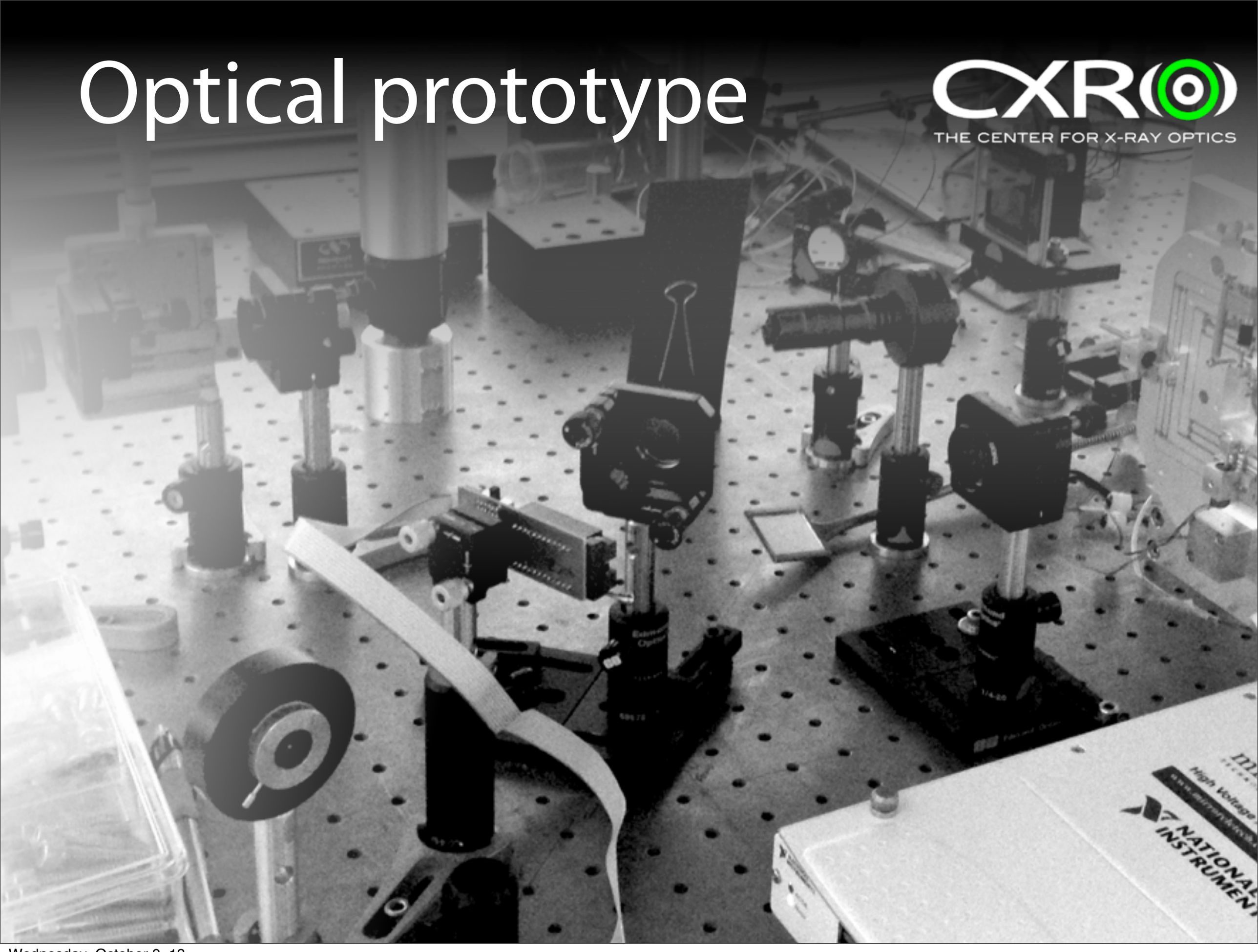
Preamp electronics



Integrated peak-hold electronics

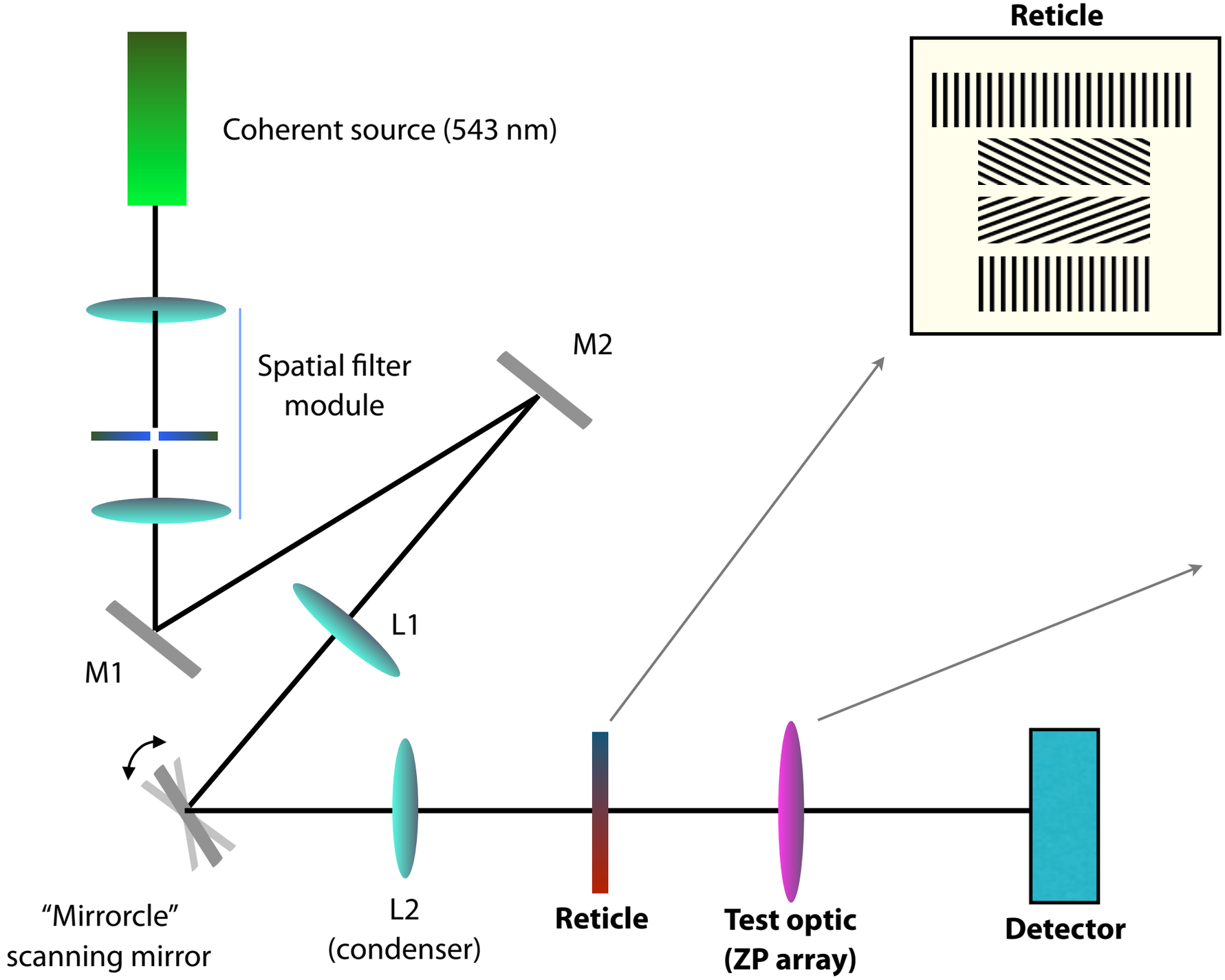


Optical prototype



Optical prototype layout

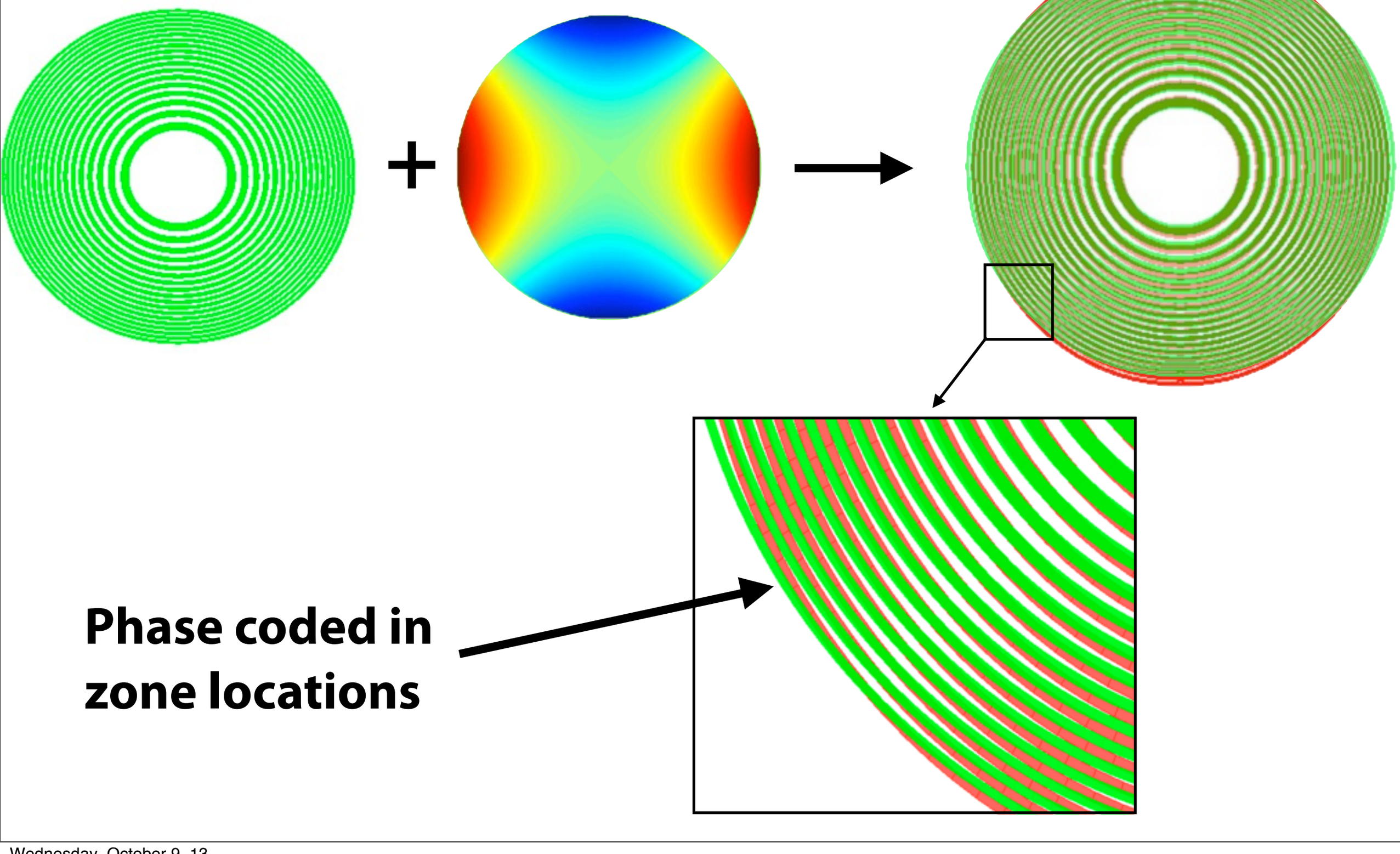
THE CENTER FOR X-RAY OPTICS



Reticle

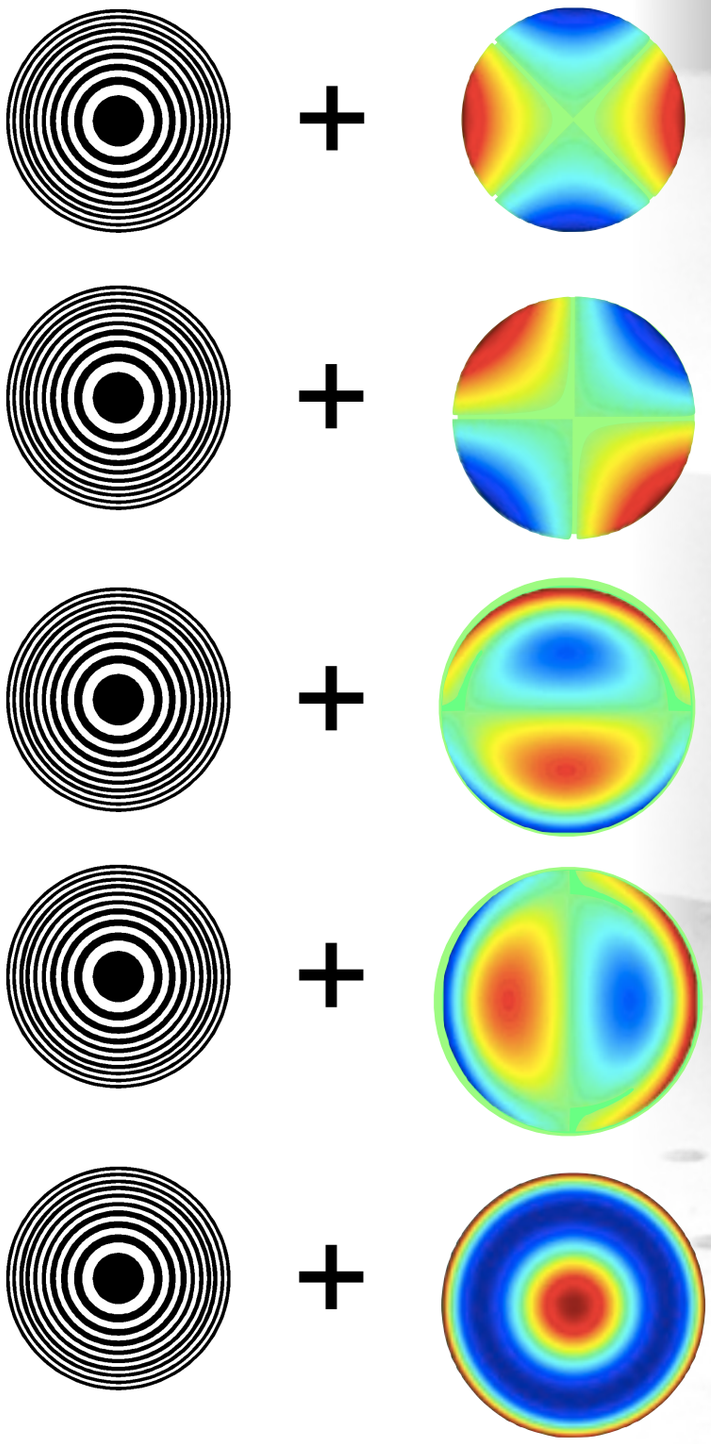
Zone plate mask

Zone plates allow programmable aberrations

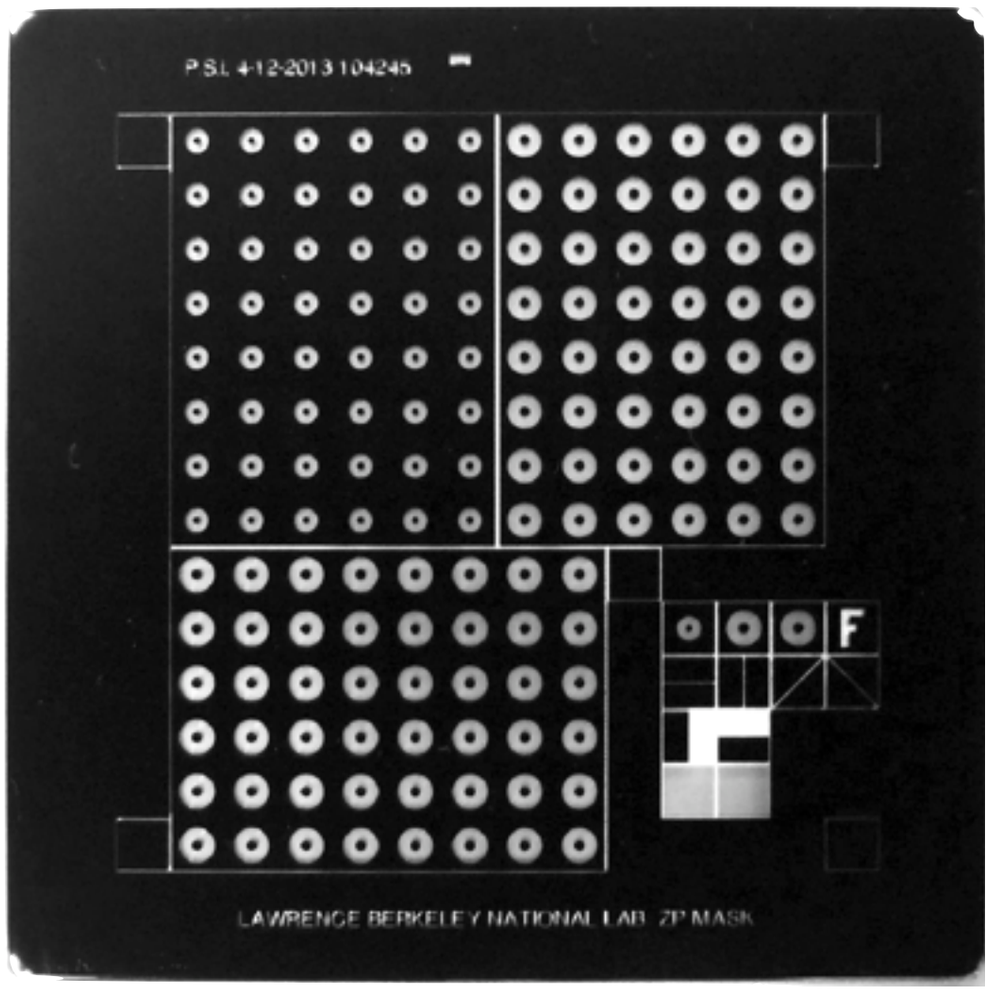


Zone plates allow programmable aberrations

THE CENTER FOR X-RAY OPTICS



Zone plate mask layout



REF	Z4 10 mWaves	Z4 20 mWaves	Z4 50 mWaves	Z4 100 mWaves	Z4 200 mWaves
Z5 20 mWaves	Z5 50 mWaves	Z5 100 mWaves	Z7 20 mWaves	Z7 50 mWaves	Z7 100 mWaves
REF	Z6 10 mWaves	Z6 20 mWaves	Z6 50 mWaves	Z6 100 mWaves	Z6 200 mWaves
Z9 20 mWaves	Z9 50 mWaves	Z9 100 mWaves	Z10 20 mWaves	Z10 50 mWaves	Z10 100 mWaves
REF	Z8 10 mWaves	Z8 20 mWaves	Z8 50 mWaves	Z8 100 mWaves	Z8 200 mWaves
Z11 20 mWaves	Z11 50 mWaves	Z12 20 mWaves	Z12 50 mWaves	Z13 20 mWaves	Z13 50 mWaves
Z14 20 mWaves	Z14 50 mWaves	Z15 20 mWaves	Z15 50 mWaves	Z1-15 20 mWaves	Z1-15 50 mWaves
REF	Z1-8 10 mWaves	Z1-8 20 mWaves	Z1-8 50 mWaves	Z1-8 100 mWaves	Z1-8 200 mWaves

Zone plate mask

- 144 Zone plates
- Programmed with Zernikes Z_4 through Z_{15} of varying amplitudes
- 3 different numerical aperture settings

Optical prototype parameters

NA: **0.2**

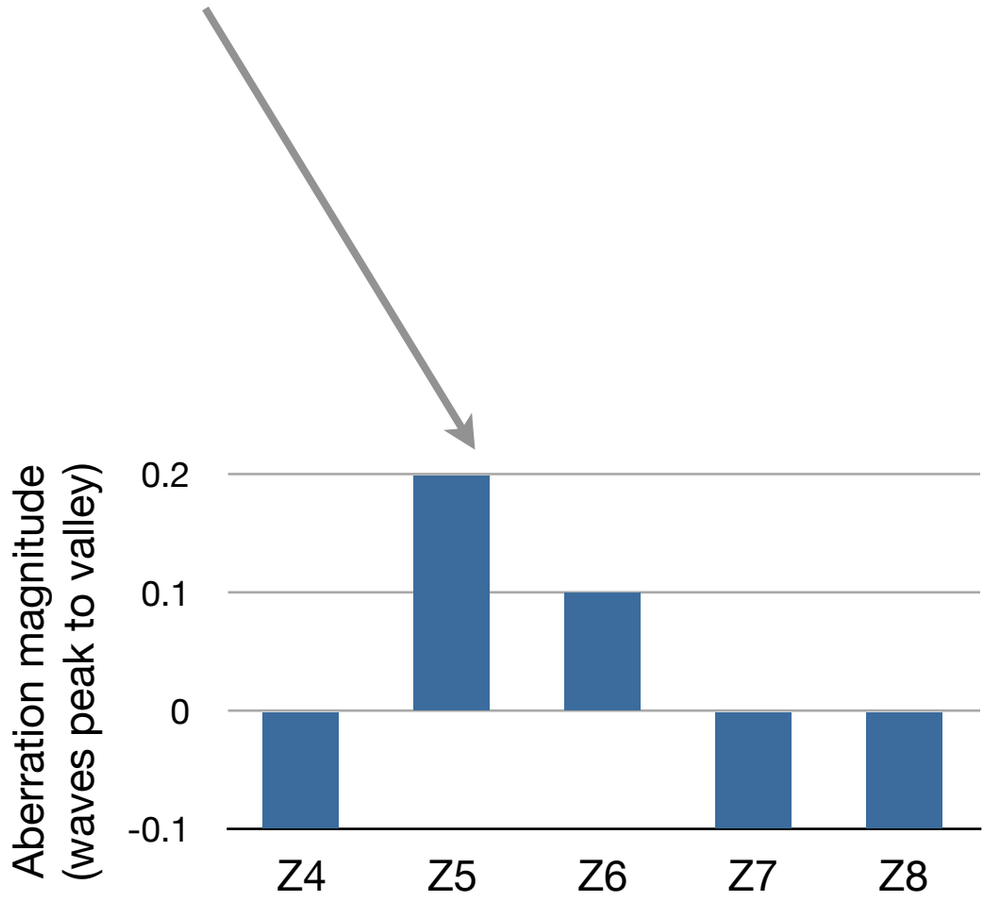
lambda: **543 nm**

Aberrations tested: **Astigmatism, Coma, Spherical, $Z_{1\text{-}8}$, Trifoil**

Probe sites: **8**, (12)

Grating orientations: **3 + 1**

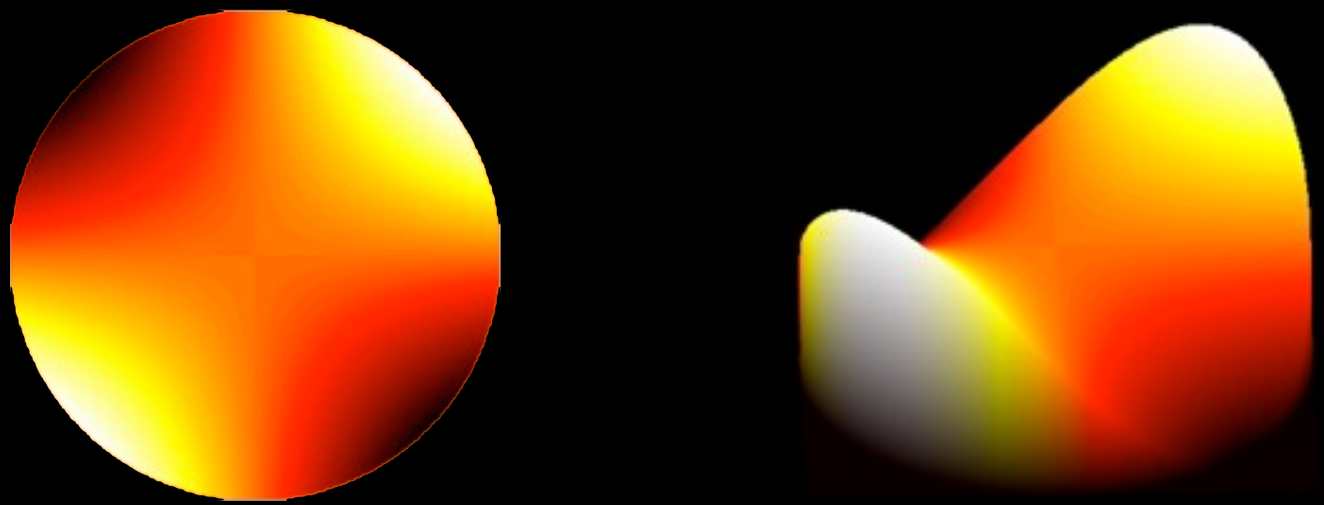
Focus steps: **21**



Astigmatism (Z_5)

THE CENTER FOR X-RAY OPTICS

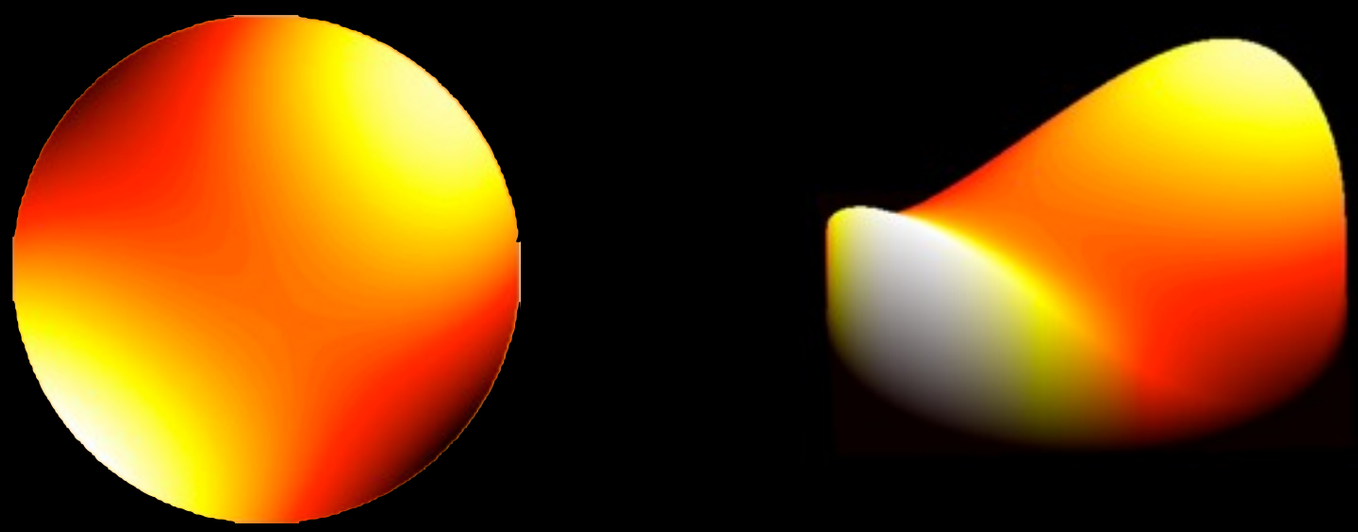
Input wave



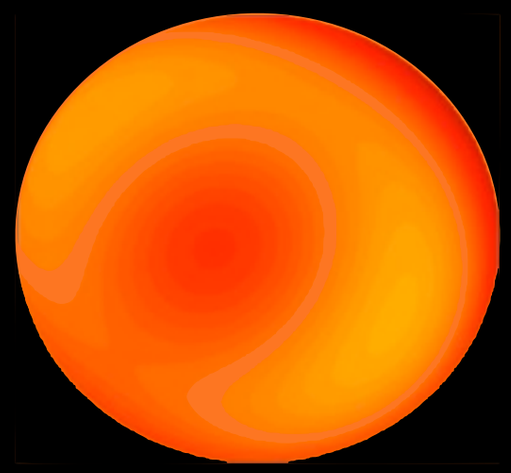
RMS error:

λ/142

AIS reconstructed wave



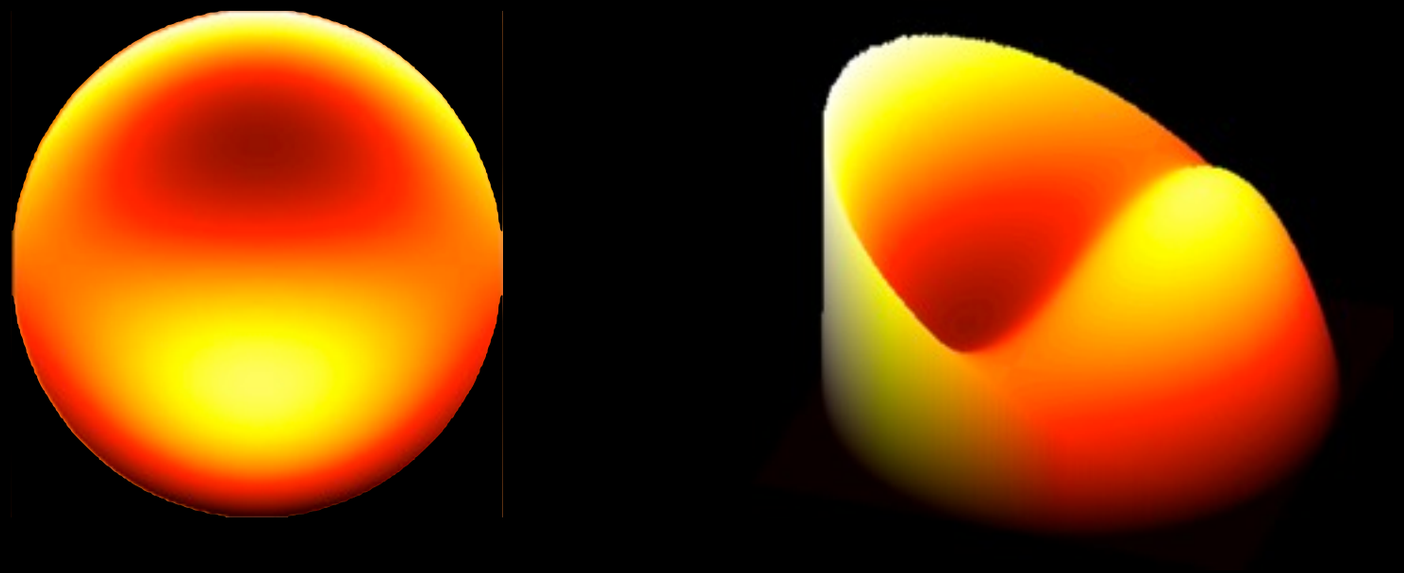
Difference



Coma (Z_7)

THE CENTER FOR X-RAY OPTICS

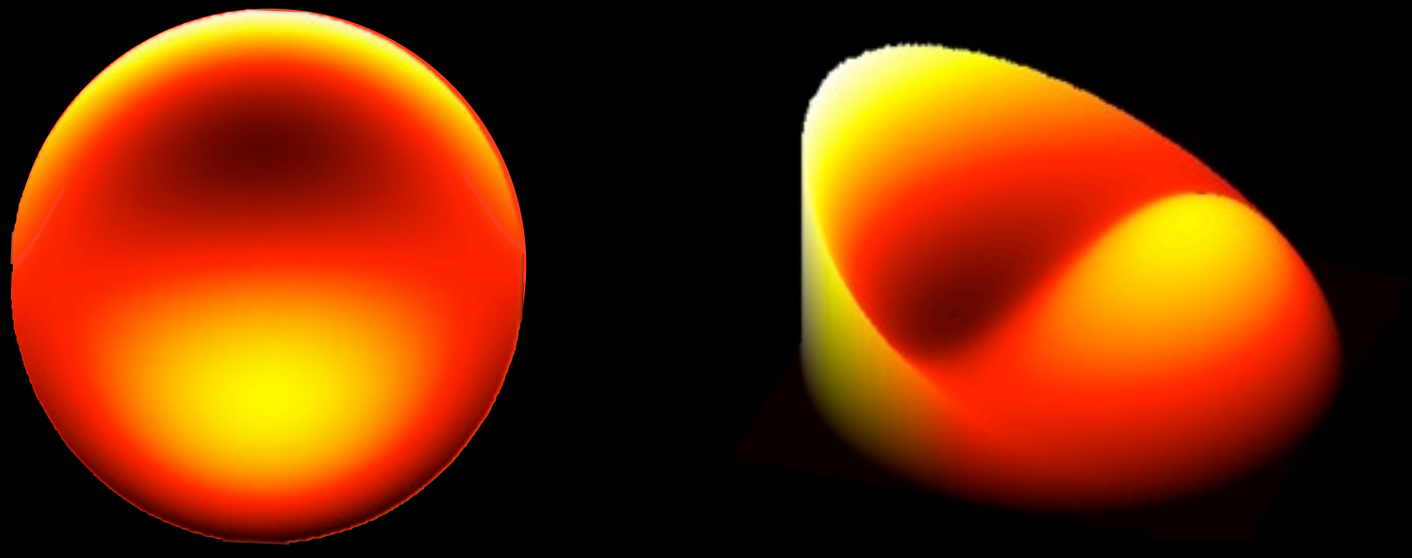
Input wave



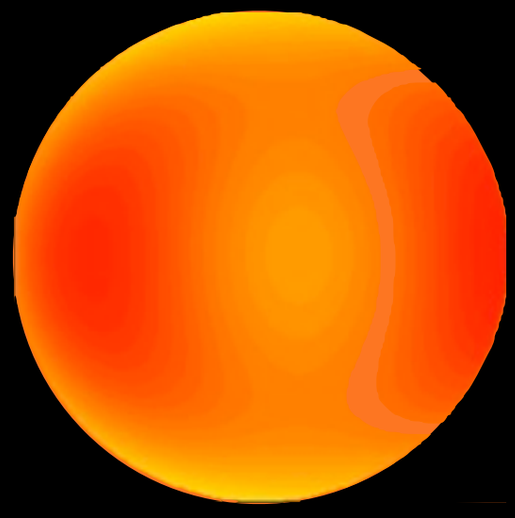
RMS error:

λ/160

AIS reconstructed wave



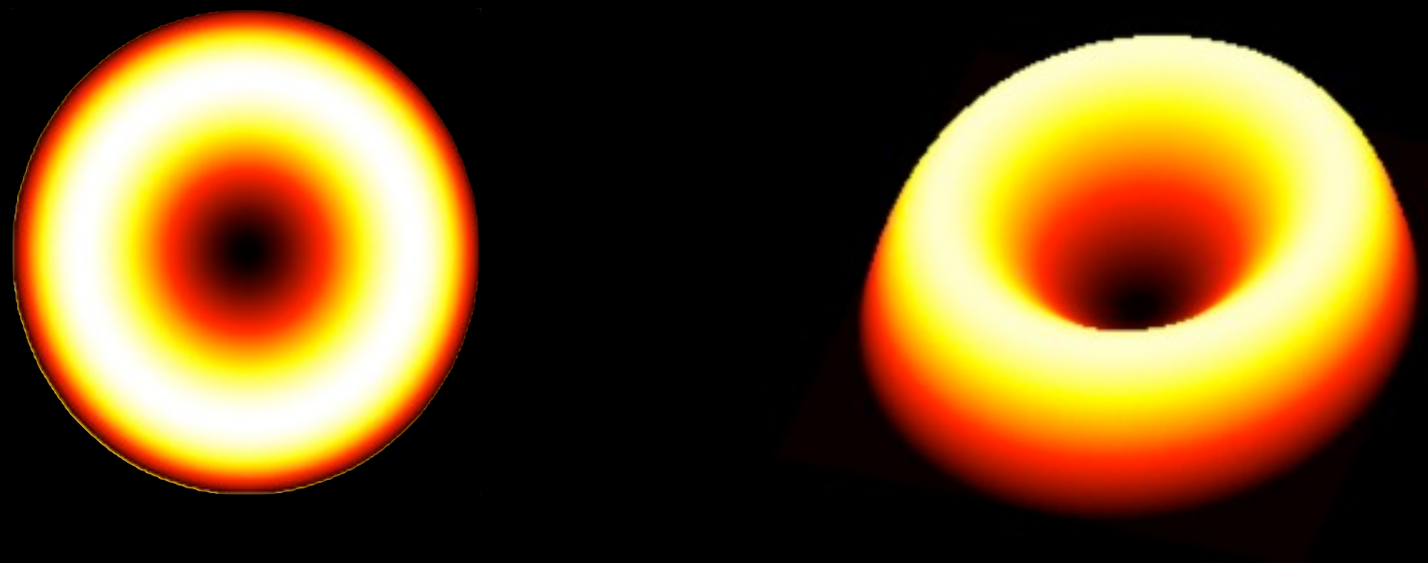
Difference



Spherical (Z_8)

THE CENTER FOR X-RAY OPTICS

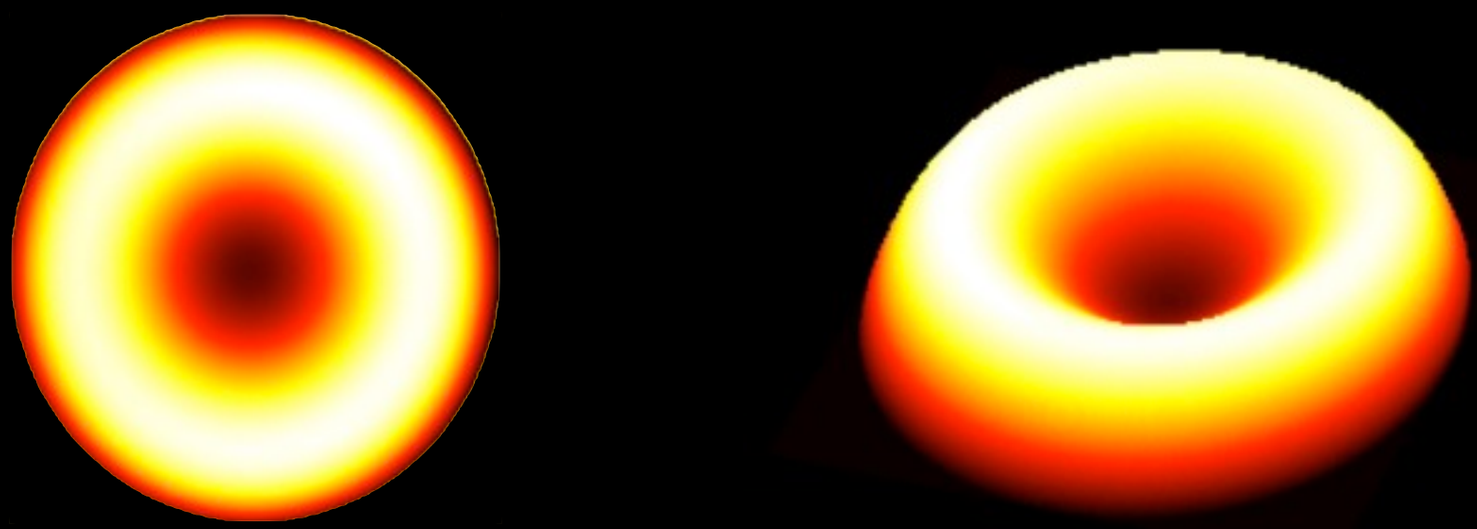
Input wave



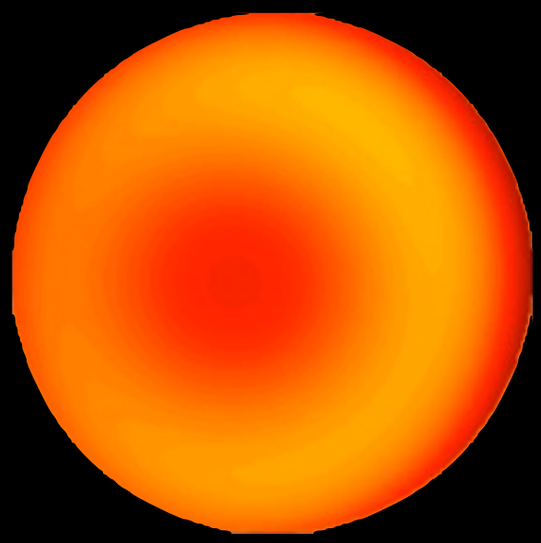
RMS error:

λ/100

AIS reconstructed wave



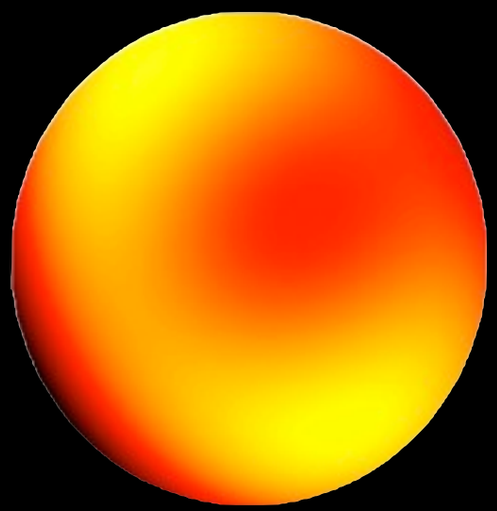
Difference

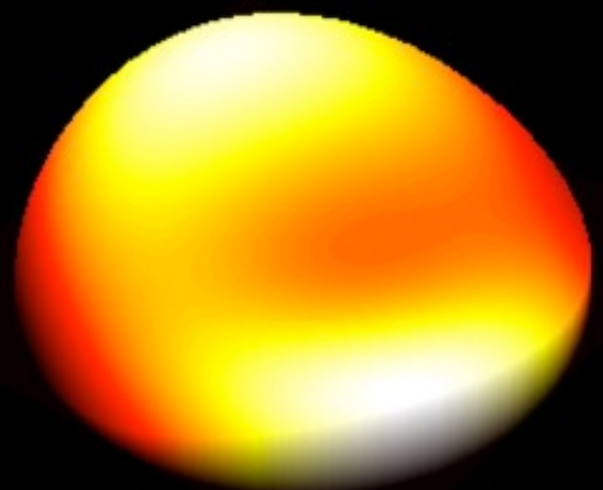


Linear combination (Z_4 - Z_8)

THE CENTER FOR X-RAY OPTICS

Input wave

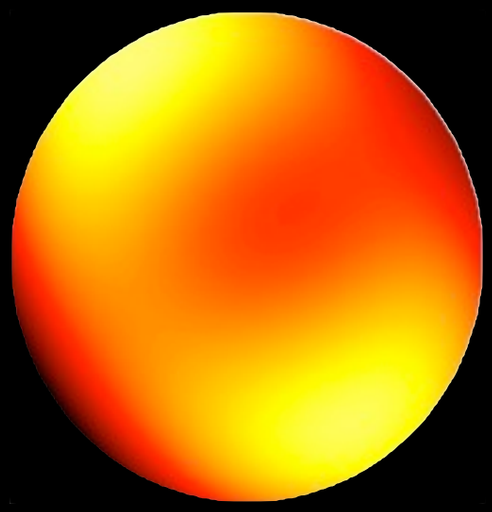


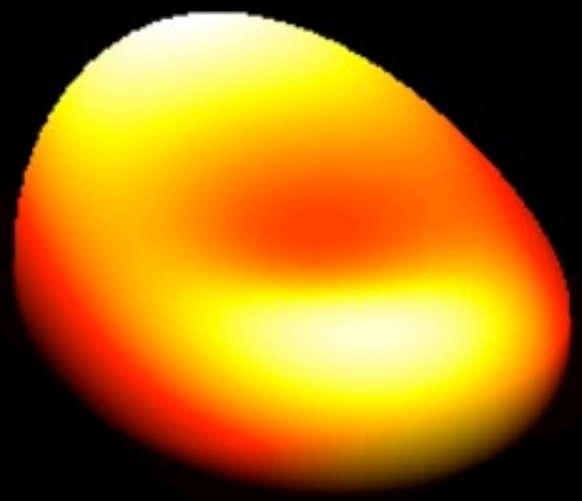


RMS error:

λ/30

AIS reconstructed wave



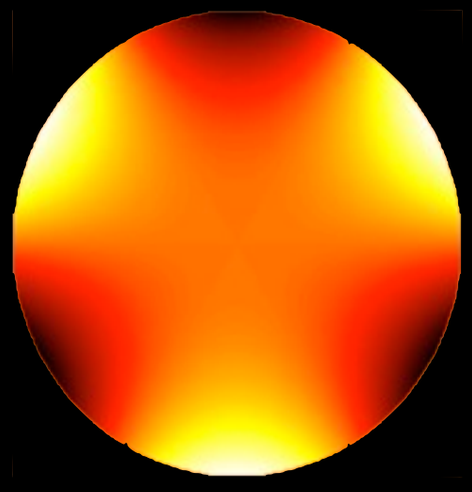


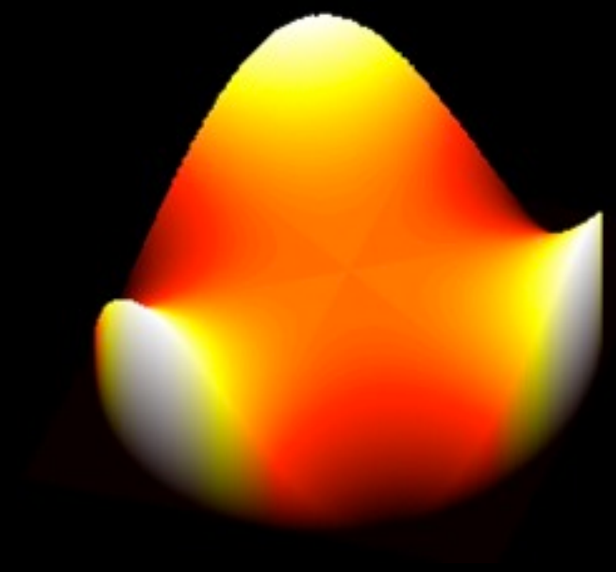
Difference

Trifoil (Z_{10})

THE CENTER FOR X-RAY OPTICS

Input wave

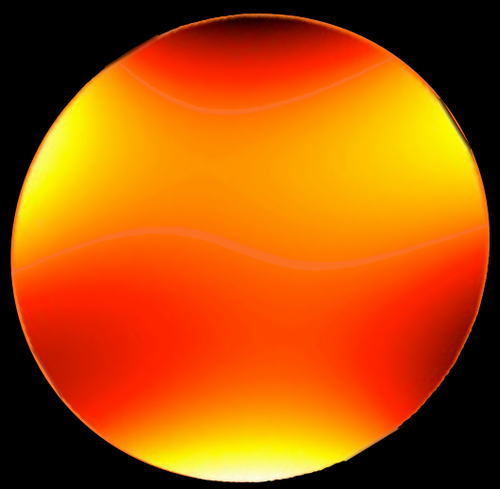


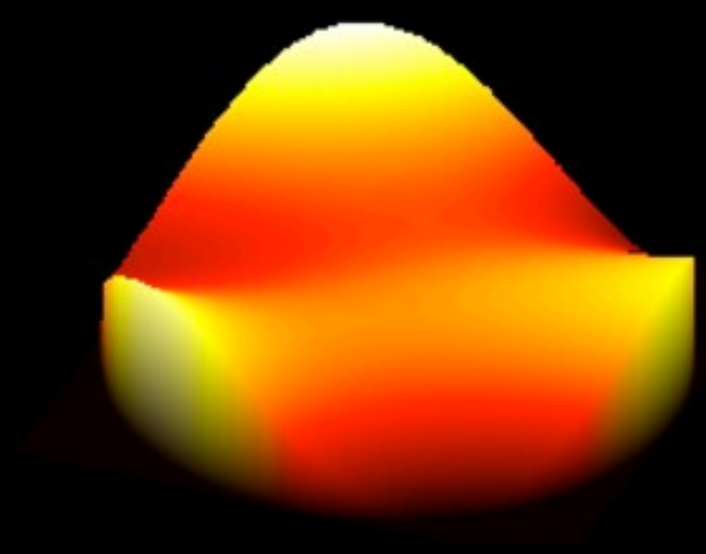


RMS error:

λ/68

AIS reconstructed wave

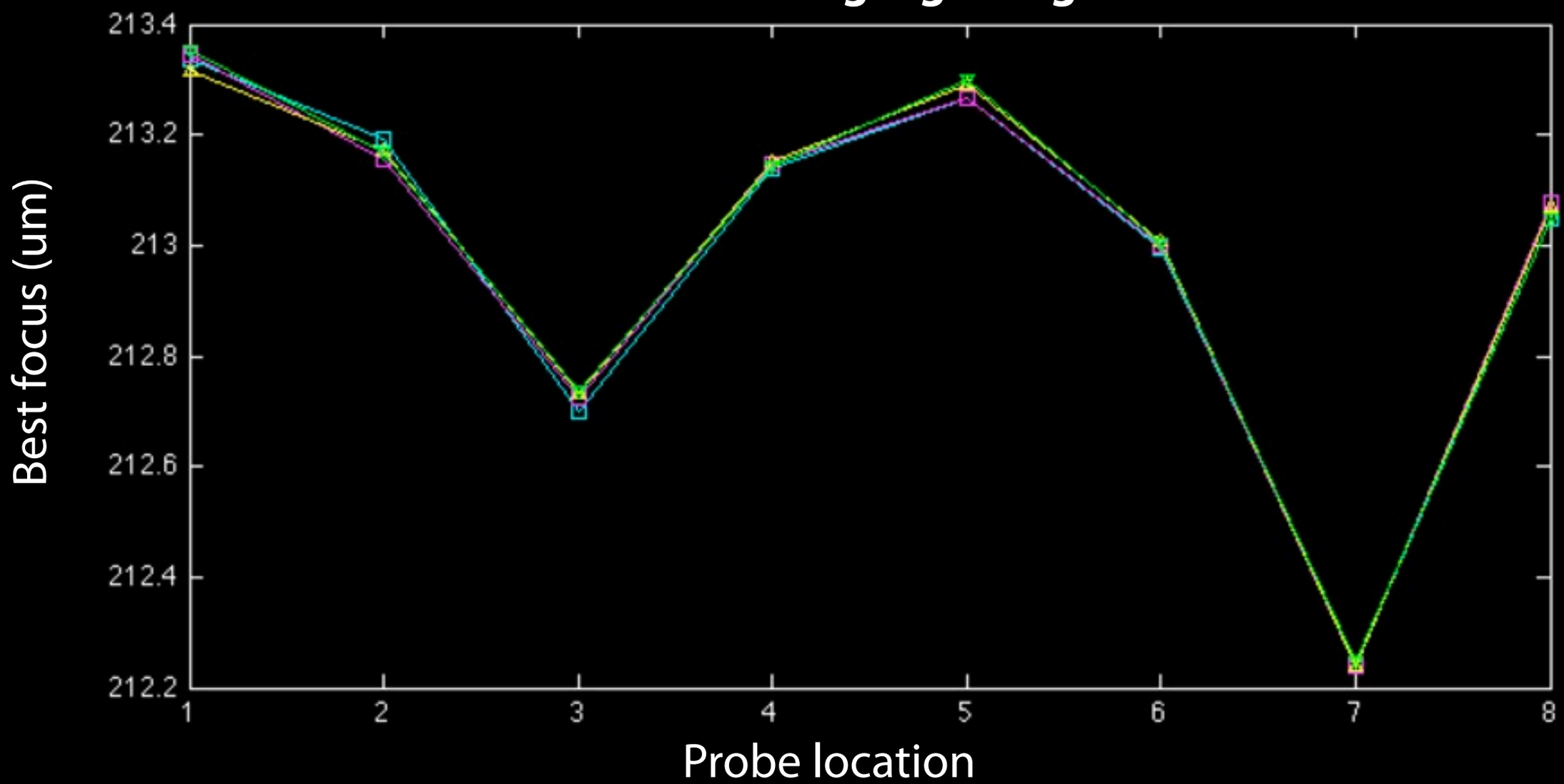




Difference

Precision

THE CENTER FOR X-RAY OPTICS

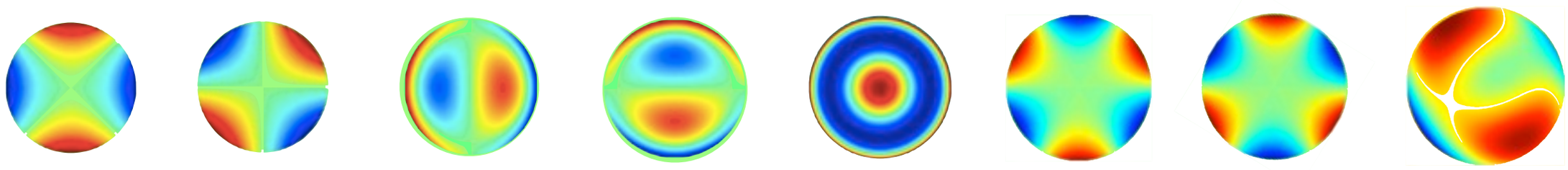


* *High stability of BF measurements.*
Accuracy of optical prototype likely limited by quality of optical elements

Precision better than **λ/150**

AIS wavefront sensor summary

- Optical demonstration of **λ/30** wavefront accuracy with better than **λ/150** precision
- Successful reconstruction of all primary Zernike polynomials as well as Trifoil



- Diode package is built and has demonstrated good noise properties.
- First EUV test planned for January in current Albany MET

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